DEVELOPMENT AND APPLICATION OF A NUMERICAL TECHNO-ECONOMIC ENERGY FORECASTING MODEL

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DEVELOPMENT AND APPLICATION OF A NUMERICAL

TECHNO-ECONOMIC ENERGY

FORECASTING MODEL

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The author is of the opinion that the quality of a dissertation is a function of at least three essential ingredients. Firstly, a problem area has to be defined which can be formulated and tailored into a practicable solution. Secondly, there should be available adequate and reliable data. Thirdly, an appreciation of the overall scope of the dissertation, as it relates to the real world, has to be always kept in sight. I am deeply indebted to the four members of the Dissertation Committee - Drs. Roger J. Schoeppel (Advisor), Larkin B. Warner, E. Lee Harrisberger and William L. Hughes - who respectively assisted me in the incorporation of the above three ingredients, although to a somewhat overlapping extent.

A special note of thanks is due Dr. Schoeppel whose intellectual inspiration, unfailing encouragement and support have opened new vistas of knowledge upon me.

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CHAPTER I

INTRODUCTION

"Nature reveals itself to man through Energy" - W. Ostwald (1)[1]

Since the beginning of agriculture, about ten thousand years ago, mankind has gradually learned to manipulate the energy supply of its biological and physical environment.[2] This has resulted in a continuous increase in both its total energy supply and population. Until about a thousand years ago, the increase in the rate of total energy consumption[3] was considerably less than the increase in the rate of population growth (2). Consequently, the biological and inorganic energy consumed per capita remained at a low, nearly constant level. This circumstance would have, perhaps, continued if a new source of energy supply - the group of fossil fuels - had not been discovered. Mining of coal as a significant energy source began about eight hundred years ago and the production of petroleum just over a century ago (3).

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[1]References are given in the Bibliography at the end of the dissertation.

[2]In the context of energy, the physical environment consists of the sun, earth, air and water as the main sources of primary energy available to man. Even the fossil fuels - coal, petroleum, natural gas, etc. - represent the storage of energy contained in vegetation matter 'fossilized' over a period of millions of years. The chemical form of energy available from the earth, in the context of agriculture, is self evident. The air, wind and water, likewise, have been known as energy sources for navigation, windmills, hydro-power generation, etc.

[3]A glossary of definitions used in this dissertation is given in Appendix A.

During the past century, the world consumption of energy from fossil fuels has reportedly increased at about four percent per year. The world's human population, however, has increased, in the recent past, at a rate of about two percent per year. Therefore, at present, the world's average (non-nutrient) per capita energy consumption is increasing at about two percent per year. It is also pertinent to note that, one half of the cumulative production of coal, during its eight hundred year production history, has been mined during the past 31 years. Likewise, half of the world's cumulative production of petroleum has occurred during the 13 year period since 1957. In brief, most of the world's consumption of fossil fuels during its entire history has occurred during the past 25 years (3).

The fact that energy undergrids all human activities is universally recognized. Also, the contribution of energy in enhancing the economic development of a country (or a region) is well documented. Because of these two main reasons, it has been customary to regard per capita energy consumption as an indicator of either the standard of living or the economic growth of a country.

The example of the United States, more than any other country in the world, is demonstrative of the extraordinary contribution which energy has made, interalia, in its technological and economic advancement. Such an advancement has required the availability of tremendous amounts of energy to meet a nearly exponential rate of fossil fuel demand during the past century. In order to meet the increasing demand, half of the cumulative coal production has occurred during the 39 year period since 1930, and half of the petroleum production during the 17 year period since 1952.

A steady exponential rate of utilization of fossil fuels implies a doubling of both, the production rate and cumulative production at equal intervals of time. Since the deposits of fossil fuels are not unlimited and, in addition, they are not renewable during time periods of less than millions of years, the rate of utilization of fossil fuels determines, to a large extent, the period over which their supplies may last. In view of the increasing U.S. energy demand, and since about two thirds of all the industrial energy is fossil-fuel based, the spectre of exhaustion of fossil fuels reserves has caused nationwide concern (4).

Looking into the future, the energy requirements of the U.S. and the world could be met by fossil fuels alone for another century. After that, dependence upon new sources of energy will become inevitable. Particularly in the case of the U.S., serious questions have been raised as to the adequacy of fuel supplies (5 , 6) for the future. All such questions are implicitly focused around energy forecasts which are essential for the formulation of policies aimed at efficient utilization of available energy resources, ensuring adequacy of supplies and evaluating plans for overall economic development.

Interest in forecasting U.S. energy requirements (sometimes referred to as demand) began about 15 years ago. About a dozen forecasts have since been published, largely in view of the governmental interest in formulating an energy policy, global and domestic changes in energy supply patterns, increased energy demand and considerations of national prosperity and security. The interest in energy forecasting has also deepened because of the recognition that historical trends of U.S. gross national product and population can be correlated with per capita and total energy consumption respectively (7).

Objective of the Study

The primary objective of this study is the development of a numerical, techno-economic forecasting model for the U.S. total energy requirements for the years 1980, 1990, 2000 and 2025. The proposed methodology is based on an engineering (systems) analysis interrelating time-series (fifty-five year period) data on total energy consumption and several aggregate, technological and economic parameters such as the gross national product, population, labor force, level and spread of technology and price per unit of energy.

It is intended to formulate the said model by identifying and quantifying those aggregate technological and economic parameters which may have interrelationship with total energy requirements. From a mathematical analysis of the data, a generalized energy forecasting model is developed which is simulated for forecasts of U.S. total energy requirements for the years 1980, 1990, 2000 and 2025. A prediction equation is derived as well.

It is also intended to show the relevance and application of the technique of dimensional analysis to the techno-economic model. However, no effort is made to use this technique in the actual formulation of the model itself.

Scope of the Study

It is almost impossible to accurately forecast the U.S. total energy requirements. However, if the interrelationships between total energy requirements and the above aggregate technological and economic parameters can be identified and quantified, it seems possible to forecast total energy requirements for a given system fairly "accurately."

The scope of this study is limited to forecasting U.S. total energy requirements for the years 1980, 1990, 2000 and 2025 -- a span of fifty-five years. These forecasts have been made on the basis of the proposed methodology utilizing relevant data for the past fifty-five year period. It can be appreciated that both, the reliability and accuracy of an energy forecast are an inverse function of its time span. Therefore, an energy forecast spanning over the next decade can be expected to be more reliable and accurate than the one spanning the next half century.

It is endeavored that the proposed methodology can afford generality in scope so that it would be applicable to forecasting total energy requirements for either an entire country such as the United States or a smaller region[4] such as the state of Oklahoma. For a given situation, the success of developing a methodology similar to the one proposed herein, depends on the astuteness with which the said inter-relationships between the aggregate technological and economic parameters can be identified and quantified.

There are several limitations of this study. For instance, no attempt is made to forecast U.S. energy requirements for individual energy sources (e.g., coal, petroleum, gas) or individual sectors. This has not been undertaken because several authors (8, 9, 10) have already reported results along these lines. Nor does this study purport to be a terminal effort in the field of energy forecasting. On the contrary, it is to be viewed as an effort to 'engineer' the complex techno-

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[4]Although the proposed methodology has not been tested in case of the Developing Countries, the author is of the opinion that it can be applied equally well in forecasting their energy requirements.

economic system resulting from the interaction of the U.S. economy and energy industry.

For the purpose of this study, a set of five aggregate technological and economic parameters was selected from amongst a total of seventeen. The criteria of their selection was the degree to which they showed functional correlations with total U.S. energy consumption data. However, the set of the five selected parameters namely, the gross national product, population, labor force, technological advancement and price per unit energy, should not be considered sacrosanct. In future, it may be possible to develop a better criterion for their selection using improved analytical techniques. In addition, no effort was made to forecast the individual parameters to the years 1980, 1990, 2000 and 2025. Since such an undertaking would have been outside the scope of this study, it was decided to utilize, in this study, the forecasts made by other authors for these parameters.

Although this study does not address itself to the formulation of a national energy policy, for the U.S., the merits of forecasting energy requirements is strongly advocated because such knowledge assists in averting the thoughtless foreclosure of policy options.

Format of the Study

This study is divided in three parts. The first part, consisting of three chapters, is intended to serve as a backdrop for the techno-economic model. The second part is primarily concerned with the statement, assumptions and development of a theoretical and an analytical framework supporting the proposed forecasting methodology. The last part is concerned with the discussion of results, conclusions and recommendations. In addition, several Appendices are included to supplement the text of this study.

The treatment of the subject of technological forecasting in general and technological energy forecasting in particular, is extensive though not exhaustive.

CHAPTER II

LITERATURE REVIEW

The analysis and development of a numerical, techno-economic energy forecasting model representing the U.S. energy-economy system lie at the interface of engineering and economics. In order to systematically cover the pertinent literature on such a model, this chapter is divided into several sections. The first section is concerned with reviewing published literature about modeling of techno-economic systems in general and the U.S. economy in particular. The second section is an overview of the subject matter of forecasting, including the description of various forecasting methods in general, and technological forecasting in particular. The third section is devoted to a brief discussion of U.S. historical energy consumption trends which have led to the current rates of energy utilization. The last section consists of the discussion of several select energy forecasts published so far.

Modeling of Techno-Economic Systems

Many scholars have sought to integrate two or more disciplines of knowledge under an academic umbrella of inter-disciplinary research. Invariably, the objective of formulating an inter-disciplinary area has been, interalia, to broaden the base of a given discipline by incorporating various analytical techniques from other disciplines.

This circumstance seems to have been more prevalent in the social sciences than in the physical sciences or Engineering of which the concepts, theories and analytical techniques have been widely applied to social sciences. Consequently, a branch of knowledge dealing with the modeling of systems at the interface of physical and social sciences has developed to its present level of sophistication. This has been made possible largely because of the application of the principles and techniques of engineering analysis of which the so-called system analysis is a specialized branch. In order to render generality to the following discussion, engineering analysis as used herein is defined as the process of formulating and solving a set of mathematical equations which describe the behavior of a collection of components of a techno-economic system which function interdependently.

One of the earliest attempts to apply system analysis was made by the English engineer Tustin (11) who, in 1953, analyzed the problem of stabilizing the British economy from the point of view of control theory as understood at that time. He concluded that more sophisticated computing machines were needed to adequately solve the set of mathematical equations describing the British economic system. About the same time, U.S. engineers Smith and Erdley (12) explored the use of analog computers in studying economic systems. With the advent of modern, large scale digital computers in about 1955, Forrester (13) applied the classical feed-back control concepts, modern decision theory and various simulations to the study of economic systems. Holland (14) has applied the above concepts to a study of national economies, particularly those of developing countries.

During the past decade, interest in modeling complex techno-economic (or even socio-economic systems) has increased considerably. Models have been developed not only for the entire U.S. economy but also for the individual industries (15). In fact, a new specialized area within economics - the econometrics - has come into existence; Samuelson, Koopmans and Stone (16) have described it as "the quantitative analysis of actual economic phenomena based on the concurrent development of theory and observation related by appropriate methods of inference."

Most of the applications cited above have resulted from the realization that the macroscopic aspects of economic systems can be described in terms of mathematical equations. These equations can be developed, in most cases, from unconstrained models of the componenets of the system itself. Indeed it can be shown that the aggregation process starting from the micro-analysis of a system to its broader macro-analysis variables also leads, in many cases, to a mathematical model of a given system (17).

In 1966, Trapeznikov (18) studied the role that technological change plays in the economic growth of a country; he considered it as a complex system consisting of a large number of elements and described it by the equation:

$$H = \alpha \ \ell n \ B$$

where H is the entropy of the system, α is a constant and B characterizes the degree of disorder in the system. He defined the parameter B as

> ... a broad concept dependent on discrepencies of material and energy flows, equipment idle times, data lags, variations in

> the size of manufactured parts, presence of admixtures in products and other reasons reducing the efficiency of the controlled complex.

More recently, Powell (19) analyzed the U.S. economy by viewing it as a multivariate process, far more complex than any found in process control industry. By identifying the components of the economy in terms of system responses, he was able to propose, "... a potential solution for effective U.S. economy control."

The foregoing remarks tend to support the view that modeling of an economic system is feasible and useful. Particularly in the case of the U.S. economy, considerable research effort has been devoted to developing simulation models which are useful in policy-making (20,21, 22). Although such models do lack perfection, they offer a significant improvement over purely qualitative bases on which policy-making had to be relied upon in the past.

An Overview of Forecasting

General Remarks

There has always been a lining of fascination about forecasts of any kind, whatsoever. These could be prophecies, speculative glimmerings of future possibilities, intuitive opinions or more recently, forecasts based on half-dozen analytical techniques such as Delphi, curve enveloping, parameter analysis, network and systems analysis, etc.

Wells (23) had forecast an era of automobiles, aviation, war, and a limitless source of energy from the atom. His finest prediction was emphasizing a science of the future - futurology, (there exists now the World Future Society). Also the celebrated works of Fuller (24), director of the World Resources Inventory group at the Southern Illinois University, are oriented toward the study of future patterns of world resource utilization.

Nearly 80 years ago, Jules Verne predicted sky travel at 600 miles per hour, submarine traffic, television, use of solar energy and even a trip to the moon departing from Florida. Also, there have been the predictions of two eminent social scientists, Ogburn (25) and Gilfillan (26) who, in the 1930's, wrote extensively on the social effects of technology. Since then, a number of economists, for example Schmookler (27), Mansfield (28) and Enos (29) have published noteworthy studies on various aspects of forecasting related to technology and economic progress.

Although the dependence of successful planning on reliable forecasting is generally recognized in the government, business and industrial circles today, often the practice of forecasting is mistaken to be a purely exploratory exercise. In the past, too, this oversight seems to have been common to both economists and engineers. The following review of forecasting techniques (or methodologies) currently in use indicates the importance now attached to forecasting.

Review of Forecasting Techniques

Cetron and Monahan (30) have classified, though arbitrarily, various forecasting techniques into the four categories listed below:

a) Intuitive Forecasting includes individual prophecy, genius forecasting, or consensus forecasting based on the opinion of a panel of experts as in the case of 'Delphi technique.'

b) Trend Extrapolation includes either the extrapolation of simple trends into the future or curve fitting on the basis of individual judgement.

c) Trend Correlation Analysis includes three main types: correlation, regression and parameter analysis.

d) Analogy Trends are related to identifying and extrapolating growth analogies taken from either the immediate past or a historical perspective.

Intuitive Forecasting is one of the most widely used forecasting techniques. There is considerable merit in this approach in view of the successful record of professionals like Jules Verne, Wells, Gilfillan, etc. However, scientists, engineers and philosophers alike have had a history of forecasting errors as well. For instance, Steinmetz advised General Electric in the 1940's that transmission systems of over 600,000 volts were not feasible; Sprague, however, proved that Steinmetz was wrong and so the General Electric Co. lost its leadership in power transmission system development for about ten years. In 1926, Bickerton (31) considered shooting at the moon as basically impossible and his view was widely endorsed by many of his contemporaries until about 1945. Likewise, Bush (32) advised the U.S. Joint Chiefs of Staff in 1945 that a high angle rocket traveling at 300 miles an hour and an atomic warhead "should be left out of our thinking for a long time."

The Consensus Forecasting technique, however, is considered safer than the intuitive forecasting although it is not always easy to have a group of experts come to a consensus of opinion. In this category, the Delphi technique is perhaps the most noteworthy. Its methodology is based on systematic solicitation of expert opinion gathered through a carefully designed program of sequential individual interrogations, interspersed with appropriate feed-back computed from previous rounds of similar solicitation of their opinions.

The technique of Trend Extrapolation has been quite popular with experts. Usually, the forecaster assumes that a past trend of an event will most likely continue in the future. There are several refinements in this methodology to accomodate for either a linear increase, an exponential increase or the increase for an S-shaped Gompertz curve.

Trend Correlation Analysis deals mainly with the trends of those technical parameters which offer difficulty in prediction by themselves or which may have correlations with two or more other parameters. Whereas time-dependent extrapolation results in explicit forecasting, trend correlation analysis of various parameters can be made on a more general level, thus evenly spreading effects of any localized anomalies in the parameters. Correlation analysis have been widely used in social sciences research problems. There is also the technique of multiple correlation and regression aimed at discerning causal factors; Simon (33) has discussed these techniques at quite some length.

Lastly, the Analogy Trend technique has been applied by many forecasters. For instance, Adams (34) considered the rate of increase in knowledge as analogous to the rate of production of inanimate energy. Such knowledge was confined to science and technology but extended to an understanding of society as well. "No one could say that the social mind now failed to respond to new force," he wrote, "even when the new force annoyed it horribly." Looking backward into the nineteenth century and forward to the beginning of the twenty-first, Adams dreamed of a new kind of America. "At the rate of progress since 1800," he prophesied, "every American who lives into the year 2000 would know how to control unlimited power." Anticipating, perhaps, the famous Einsteinian equation, Adams was confident that ultimately inanimate energy would be technologically limitless. Once he had such control over matter and energy, Adams believed the American of the twenty-first century "... would think in complexities unimaginable to an earlier mind. He would deal with problems altogether beyond the range of earlier society" (34). Likewise, Hartman (35) developed a forecasting model for new knowledge by considering it analogous to the behavior of gas molecules in a reaction process. To him, the molecules are analogous to either the scientists or pieces of information, both occuring at a given volume density. The scientist-molecules do not move significantly, whereas the information-molecules move with an assumed constant velocity. A useful reaction supposedly occurs when the "scientist-molecules have a reaction cross-section which is hit by the information-molecules."

In the area of historical analogy studies, most of the work has been done by Helmer (36) and Fisher (37).

Technological Forecasting

Technological forecasting, in contrast to economic forecasting, implies that due consideration be given to the impact of technological changes in a given economy. The success with which technological forecasts can be made depends on the intuitive judgement of the forecaster and his ability to identify and quantify the interrelationship among the significant parameters affecting the event under forecast.

The phenomenal growth of science and technology has afforded many new decision options to policy-makers, requiring a higher degree of selectivity on their part. Choices between alternative plans may make vast differences in their outcome or competitive performance. Also, science and technology are being recognized as having strong influences on the society itself. Since science and technology are dependent upon availability of adequate energy resources, the governments, therefore, must strive to forecast and formulate national energy needs and policies, respectively.

Interest in technological forecasting began about twenty five years ago in the U.S. Lenz (38) has stressed the need for technological forecasting thus:

> The literal situation of no-forecast...implies that each action is unrelated to any past experience, present situation, or future intended action. The price of this insanity is non-survival, yet it is practiced to some degree in organizations prone to frequent changes in management. The obvious error in a no-forecast is that all action is random, limited only by the extremes of possible alternatives.

A study of the various areas to which technological forecasting has been successfully applied by economists and engineers presents a variegated array as shown in Appendix B ; some contemporary issues to which technological forecasting has been addressed to are:

a) Will atomic energy be competitive with coal? If so, when?

b) Is the electric automobile going to be feasible? Will some other fuel such as hydrogen become economically feasible for vehicular use?

c) Does aluminum technology threaten steel's future?

d) Will the SST become a reality?

e) Can paper become a raw material for making cloth and furniture?

Questions like these indicate that technological substitution is bound to have wide-spread impact on the future way of life in general and economic growth in particular. Recently, a number of governmental agencies, notably the National Science Foundation, the Department of Defense, National Aeronautical and Space Administration (NASA) and several private organizations such as the Resources for the Future, Inc. (RFF), Stanford Research Institute (SRI), etc., all have contributed to the general area of technological forecasting. Cetron (30) has compiled a comprehensive bibliography listing some three hundred and eighty references, most of which were published during the past decade; it seems neither necessary nor practicable to review all these references. However, the works of Lenz (38), Ayers (39), Brown (40), Helmer (35), Linstone (41) and Mottley (42) are generally considered to be of a pioneering nature.

Lenz was perhaps the first engineer to develop a technological forecasting model by using analytical techniques such as trend extrapolation; he emphasized the role of "...informed judgement of scientific and technical expertise..." in technological forecasting. Isenson and Cetron, too, made noteworthy contributions; Isenson directed the U.S. Army's widely publicized project HINDSIGHT (which was probably the most extensive study of U.S. technological progress) and Cetron pointed out that the concept of technological forecasting is only the first step in successful planning. These authors have been associated with the Department of Defense whose former head, McNamara (43) spoke of technological forecasting as "quantitative common sense," and added:

> I would not, if I could, attempt to substitute analytical techniques for judgement based on experience. The very development and use of those techniques have placed an even greater premium on that experience and judgement, as issues have been clarified, and basic problems exposed to dispassionate examination. The better the factual bases for reflective judgement, the better the judgement is likely to be. The need to provide the factual basis is the reason for emphasizing the analytical approach.

Recently, three comprehensive books on technological forecasting have been published. These are by Bright (44), Butler and Kavesh (45) and Jantsch (46). The first two contain technical contributions by some thirty of the nation's foremost experts on technological forecasting. Jantsch's work is perhaps the most comprehensive work to date; he studied technological forecasting throughout the world, surveyed some four hundred references in the literature and identified about 100 technological forecasting and planning projects currently in progress in thirteen countries. He specifically listed the U.S. military as the leader in this field and estimated that approximately $60 million is spent yearly on making technological forecasts in the U.S.

Past and Current Trends in U.S. Energy Economy System

Past Production and Consumption Trends

In reviewing the history of U.S. energy consumption, it is evident that in 1870, about 76 percent of the total energy requirements were met by wood as the primary fuel. From about 1870 to 1910, the U.S. production of coal and lignite followed a nearly constant exponential growth rate of 6.5 percent per year with a doubling period of 10.6 years. Due to the inevitable process of inter-fuel substitution, coal had displaced wood as the primary fuel by the turn of the twentieth century. From about 1910 to date, the U.S. production of coal and lignite has averaged around five hundred and fifty million short tons per year. This is shown in Figure 1.

The dynamics of inter-fuel substitution were evidenced again in the late 1950's when oil displaced coal as the primary fuel. The U.S. crude-oil production from 1870 to 1930 increased at a rate of about 8.3 percent per year with a doubling period of 8.4 years, as shown in Figure 2. Since 1930, the crude-oil production curve has shown a leveling trend largely because of the entry of natural gas on the energy scene. From about 1905 to 1965, the production of marketed natural gas has increased at an almost constant exponential rate of 6.6 percent per year with a doubling period of 10.5 years. This is shown in Figure 3.

The U.S. production of total energy from coal, oil, natural gas and hydro-power shows two distinct growth periods. From about 1850 to 1907, the growth rate of energy production was 6.9 percent per year with a doubling period of about 10 years. Then from 1907 to present, the growth rate has dropped to about 1.77 percent per year with a doubling period of 39 years. This is shown in Figure 4.

In 1970, about 76 percent of the U.S. total energy requirements were supplied from oil and natural gas (43 and 33 percent, respectively), 20 percent from bituminous coal, 3.4 percent from hydro-power and about 0.3 percent each from nuclear energy and anthracite coal (47). The increased demand for electrical energy in the U.S. has averaged almost 7 percent per year during the 1960's (48). The U.S. consumed over 1500 billion kwh of electricity in 1970. By the year 1980, the demand is forecast to double; and, if this doubling continues to the year 2000,

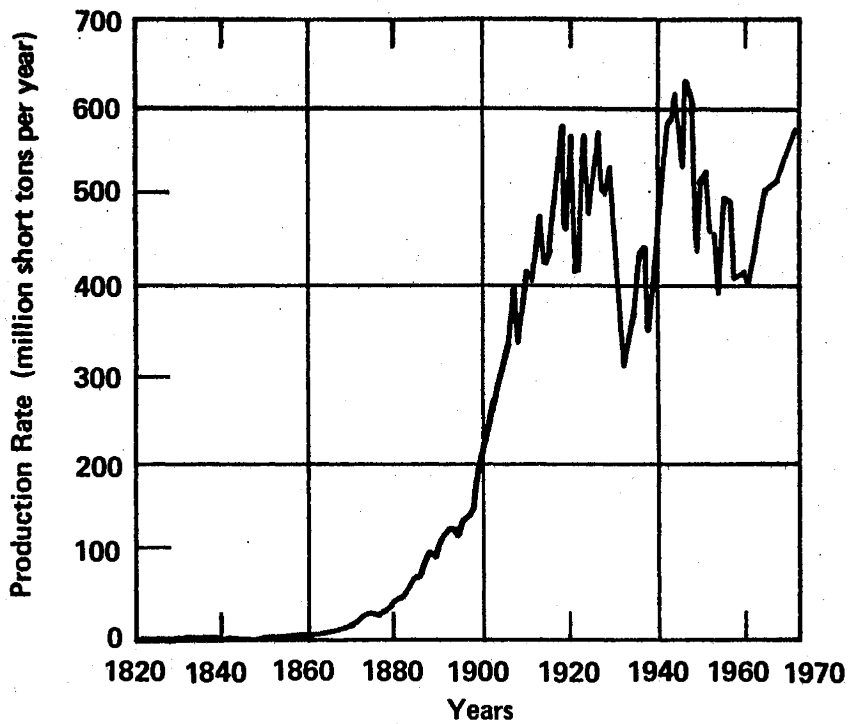

FIGURE 1 U. S. PRODUCTION OF COAL AND LIGNITE DURING 1820-1970

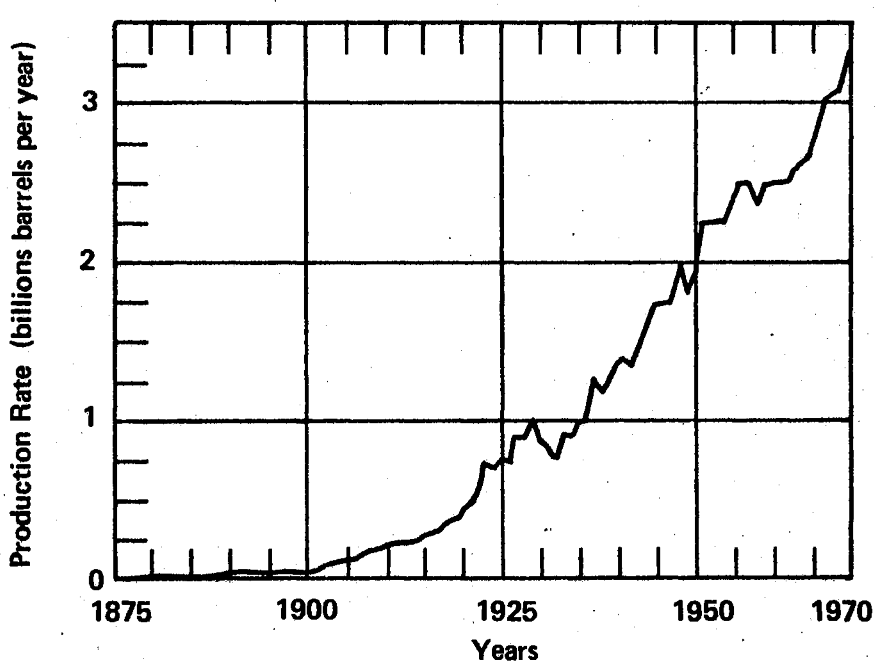

FIGURE 2. U. S. PRODUCTION OF CRUDE OIL DURING 1875-1970

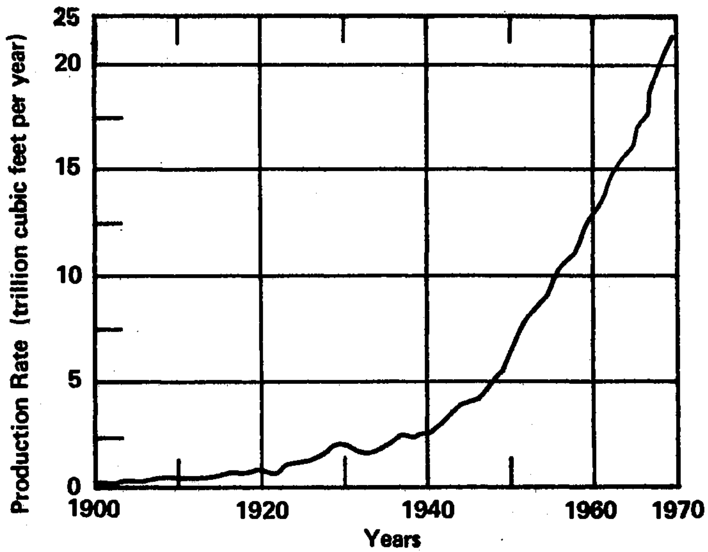

FIGURE 3. U. S. PRODUCTION OF (MARKETED) NATURAL GAS DURING 1900-1970

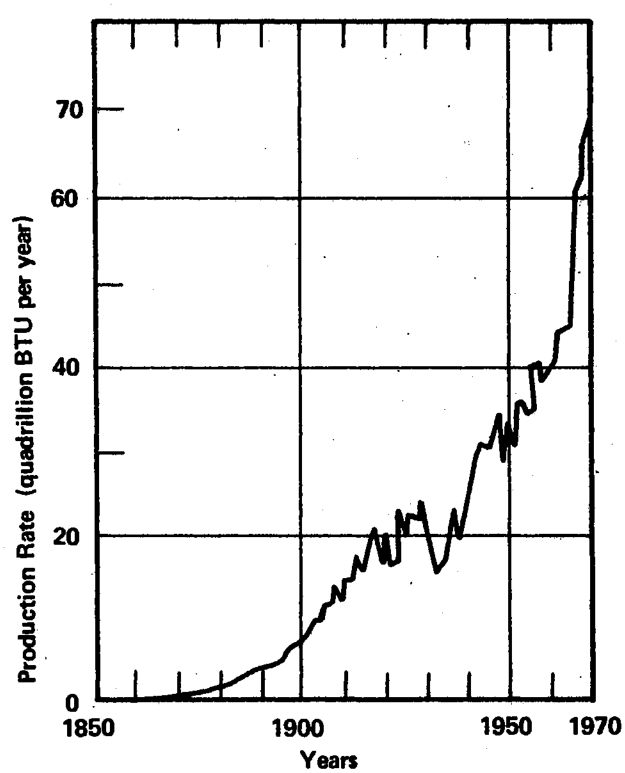

FIGURE 4. U. S. PRODUCTION OF THERMAL ENERGY FROM COAL, OIL, GAS AND HYDRO-POWER DURING 1850-1970

the U.S. electrical energy requirements will be 10,000 billion kwh, at a load factor of 0.68 and average heat rate of 8000 BTU/kwh. Graham (49) has reviewed the past U.S. energy consumption trends by individual fuels as well as for total energy. During the past century (1870-1970) the U.S. total energy increased about sixteen times amounting to 68.8 quadrillion (10^{15}) BTU in 1970. In comparison, the U.S. population increased only about three times during the same period; therefore, U.S. per capita energy consumption increased slightly more than five times during the past century to its current value of 325 million BTU.

A Short Review of U.S. Energy Forecasts

> ... But nowhere on the horizon is there a saturation point for energy. Its future is limitless. It not only marches to ever greater quantitative output, but it also transforms the entire economic structure as it goes. --- Chase (2)

While reviewing the literature it became apparent that several agencies of the U.S. Government have long been active in energy forecasting. Of these, the Office of Science and Technology (Executive Office of the President), the United States Bureau of Mines, various committees of the U.S. Senate, and the Atomic Energy Commission are most noteworthy. Comprehensive studies have also been published by Resources for the Future, Inc. (10), Stanford Research Institute (50) and Battelle Memorial Institute (51).

Since a comprehensive listing of all the U.S. total energy forecasts made to date was not considered practicable, it was decided to incorporate here a partial chronological list of the eighteen select U.S. total energy forecasts shown in Table I. The quality of an energy forecast, like any other forecast, is limited by the astuteness of the

TABLE I

SELECTED U.S. TOTAL ENERGY FORECASTS

	NAME OF AUTHOR/SOURCE	BIBLIOGRAPHY #	DATE OF PUBLICATION	BASE YEAR	FORECAST IN QUADRILLION (10^{15}) BTU'S FOR THE YEARS				CORRELATING VARIABLE USED				
					1970	1980	2000	2025	GNP	Population	Fuel form	Fuel end-use	Electricity
1	Texas Eastern Trans. Corp.	8	1968	1947-65	64.4	97.8				X	X	X	
2	U.S. Bureau of Mines	9	1968	1947-65	64.3	88.1	168.6		X	X	X	X	
3	Chase Manhattan Bank	52	1968	1950-65		97.0							
4	Strout, Allan M.*	53	1968	1960		90.3	174.0			X			
						(99.7)	(213.0)						
5	Sartorious and Co.	54	1967	1960-65	60.8	93.3				X	X		X
6	Stanford Research Institute	50	1967	1965		97.0				X	X	X	
7	Fremont, Felix**	55	1964	1961		70.3	110.6	252.2	X	X			
8	Resources for the Future	10	1963	1960	60.2	79.2	135.2		X	X	X	X	X
9	U.S. Atomic Energy Comm.	56	1962	1907-60		82.0	135			X			X
10	National Academy of Sc.	57	1962	1907-60		61.0							
11	Lasky Study Group	58	1962			82.0				X	X		X
12	Teitelbaum, P.D.	59	1961	1958		80.9				X	X		X
13	Texas Eastern Trans. Corp.	8	1961	1958		82.6				X	X	X	X
14	U.S. Atomic Energy Comm.	60	1960	1953		86.2	170.0			X	X		
15	Sporn, Philip	61	1959	1959			105.0			X	X		X
16	U.S. Bureau of Mines	62	1956			72.5						X	
17	U.S. Atomic Energy Comm.	56	1953	1947		87.6	150.0						
18	Paley Commission	63	1952							X	X	X	X

*Energy estimates assuming 3.5 percent growth rate in GNP and (4.0 percent per year).
**Felix used National Income as a variable.

assumptions upon which it is based. Almost all the authors of the forecasts in Table 1 did not explicitly state all the assumptions. Nor did they give sufficient details of their methodologies, let alone the terminological inconsistencies. However, it seems possible to classify nearly all the assumptions made in the above forecasts into the following seven categories:

a) Gross National Product - the assumptions usually refer to real growth rate ranging from 3.5 to 5 percent per year for the U.S. economy.

b) Population - the assumptions refer to the U.S. Bureau of Census projections with 1.6 percent per year growth rate.

c) Prices of Fuels - the assumptions refer to fuel prices relative to a general price level in the U.S. It is also generally assumed that the relative prices remain at the same competitive levels (9).

d) Availability of Fuels - it is invariably assumed that there will be no limitation to either the availability or supply of various fuels needed to meet the U.S. energy requirements.

e) Technological Change - in most cases, technological change is not included as a variable. However, many forecasts assume that gradual displacement of fossil fuels by nuclear fuels will occur in the foreseeable future.

f) The influences of business cycle swings are assumed to be minor.

g) Present considerations of national security are assumed to continue up to at least the end of this century.

The eighteen forecasts for total U.S. energy requirements range from 61.0 to 99.7 quadrillion (10^{15}) BTU for the year 1980, and from 105.0 to 213.0 quadrillion BTU for the year 2000; this shows a variation of about 60 percent for 1980 and about 103 percent for the year 2000. These ranges of variations explain why energy forecasting is still considered to be more of an art than science!

A list of eight selected U.S. energy forecasts showing the relative shares of individual energy sources is given in Table II. From these forecasts it is seen that the average percentage share of coal is expected to gradually decrease; the relative share of coal ranges from 15.77 to 21 quadrillion BTU (606 to 800 million tons of coal) for the year 1980, and from 17.96 to 27.2 quadrillion BTU (700 to about 1,050 million tons of coal) for the year 2000. In the case of petroleum, the forecasts project a slightly increasing growth rate up to the year 1980 and a gradual decline thereafter. The range of forecasts varies from about 30 to 40.17 quadrillion BTU (5.17 to 6.93 billion barrels) for the year 1980 and from 57.6 to 61.67 quadrillion BTU (10.0 to 10.66 billion barrels) for the year 2000. The forecasts for the relative shares of natural gas demand show slightly declining trends up to the year 1980, followed by a rapid decline to the year 2000.

In case of nuclear energy requirements, there is a wide range of forecasts: from 2 to 13.3 quadrillion BTU (67,000 to 442,000 megawatts) of nuclear generating capacity is forecast for the year 1980, and from 8.81 to 43.53 quadrillion BTU (295,000 to 1,410,000 megawatts) for the year 2000.

TABLE II

U.S. ENERGY FORECASTS FOR INDIVIDUAL ENERGY SOURCES, QUADRILLION (10^{15}) BTU

	NAME OF AUTHOR/SOURCE	BIBLIOGRAPHY #	COAL		PETROLEUM & NGL		NATURAL GAS		NUCLEAR		HYDRO-POWER	
			1980	2000	1980	2000	1980	2000	1980	2000	1980	2000
1	U.S. Senate (1962)	58	21 (25.6)*	-	33.0 (40.2)	-	22.78 (27.8)	-	2.0	-	2.0	-
2	U.S. Bureau of Mines (1964)	64	16.34 (19.1)	-	36.04 (41.9)	-	25.52 (29.7)	-	4.36 (5.1)	-	2.67 (3.1)	-
3	Sartorius and Co. (1967)	54	16.02 (17.1)	-	29.94 (32.1)	-	33.03 (35.4)	-	13.3 (14.3)	-	3.0 (3.2)	-
4	Texas Eastern Trans. Corp. (1968)	8	19.88 (20.3)	-	40.17 (41.1)	-	31.89 (32.6)	-	4.76 (4.9)	8.81 (7.4)	3.06 (3.1)	-
5	U.S. Atomic Energy Comm. (1960)	60	25.5 (29.7)	62.0 (36.5)	38.0 (44.1)	71.0 (41.8)	20.0 (23.2)	34.0 (20.0)	-	-	2.58 (3.0)	2.55 (1.5)
6	Resources for the Future (1963)	10	15.77 (19.9)	17.96 (13.3)	32.91 (41.6)	61.67 (45.6)	24.15 (30.5)	33.81 (25.0)	3.7 (4.7)	19.0 (14.1)	2.64 (3.33)	2.82 (2.1)
7	Public Land Law Review Comm. (1968)	65	18.4 (20.7)	27.2 (18.0)	30.3 (34.7)	52.8 (35.0)	28.0 (31.5)	43.6 (28.9)	8.2 (9.4)	-	-	-
8	U.S. Bureau of Mines (1968)	9	19.3 (21.8)	22.4 (13.3)	35.58 (40.8)	57.6 (34.3)	24.46 (28.9)	41.7 (24.7)	4.08 (4.6)	43.53 (25.8)	3.03 (3.4)	5.06 (3.0)

Remarks:

* The figures in the parenthesis indicate percentage shares for various fuels.
a. Totals may not add to 100 due to rounding of data.
b. One barrel of oil assumed to equal 5.8 million BTU.
c. One cubic foot of natural gas assumed to equal 1,035 BTU.
d. The heat rates for nuclear and hydro-power assumed as 9,320 and 7,860 BTU/kwh for 1980 and 2000 respectively.

Review of Energy Forecasting Methodologies

The set of forecasts presented in Tables I and II have differences in methodology, preferences of forecasters, time available for their preparation, and the time span for which they were intended. Therefore, the criterion of accuracy should be viewed only in a relative setting and, rigorously speaking, the criterion of a forecast being reasonable rather than accurate seems more justified.

Nearly all the eighteen forecasts in Table I endeavor to incorporate, with varying degrees of success, some basic parameters known to correlate with energy demand; one such parameter is population, but its value as a correlating parameter is based on the assumption that supply of energy sources will be commensurate with per capita needs. Also energy consumption has been shown (7, 8, 55) to have positive correlation with factors determining standard of living.

Several forecasting methods can be identified among the eighteen forecasts; the simplest method is to project historical, time-series U.S. total energy consumption data into the future. The success of this method depends upon the selection of an appropriate time span over which historical trends could be assumed fairly consistent. The Paley Commission's (63) report in 1952 and National Academy of Sciences forecast (57) are examples of this type. This method gives, relatively speaking, reliable results for short-term and may be used exclusively for total energy forecasting. A somewhat sophisticated version involves the correlation of U.S. population with per capita energy consumption. The U.S. Atomic Energy Commission forecast (60) in 1960, and an earlier one by Putnam (51) in 1953, are noteworthy examples.

Another technique termed as technological energy forecasting has been utilized in a comprehensive work (10) by the Resources for the Future (RFF). Basically the RFF study used a building block approach starting with 1960 as the base year for the various consuming (end-use) sectors of the U.S. economy. Projections were made for the years 1970, 1980, 1990 and 2000. The projected demand figures were then subdivided into various sources of energy according to their future relative shares.

The U.S. Department of Interior study (9) was based on a least squares projection of U.S. energy consumption data for 1947-65. From these data, appropriate trends were calculated for total energy consumption and for various energy forms (direct fuel, utility electricity and raw material non-fuel and non-power) sectors and sources. These trends, extrapolated into the future, were subsequently altered by techniques which "varied accordingly to the energy components being projected." The authors stated that, "Procedures for the forecasts may be described as opportunistic in that various types of methods and techniques are used"; however, an energy forecasting model with relevant parameter estimates, assumptions and its limitations was not explicitly stated.

Strout (53) used a linear, multiple regression model for the U.S. economy. After testing several variables for significance, accuracy and other variants of form (such as the log linear) for the model, he concluded that the linear model was found to be the simplest and at least as satisfactory as others. The explicit form of his model was:

$$\frac{F_c}{P} = 1.8757 + 0.0082\, F_{DD} + 0.1148\, \frac{Y_P}{P} - 0.00097t$$

where,

F_c is per capita fuel use in quadrillion BTU.

P is population, millions of people.

F_{DD} is average fuel degree-day for "thirty-six metropolitan areas weighted by the nearest decinnial census."

Y_P is private gross national product of the U.S. in 1954 dollars, excluding the general government spending.

t is the time series (1921, 22, 23, ... 1980, ... 2000).

Quite a few forecasts included low, medium and high range of estimates; the medium one represented a "best estimate" and the low to high range was considered as a reflection of the uncertainty associated with a given forecast. However, no statement was made concerning the confidence to be placed in these limits. The range of low-medium-high estimates were generally within ±10 to ±20 percent.

Miscellaneous Aspects of Forecasts

Comparison of Energy Forecasts

The literature survey on energy forecasting reveals several conceptual and terminological differences between the various forecasts. These differences becloud comparisons and a simple consistent adjustment can not be devised to remove their differences. Furthermore, differences in assumptions (most of which were implicitly incorporated and few, if any, were stated quantitatively) and data base years introduce additional difficulties. However, several energy forecasting methodologies are available; the simplest one is concerned with projecting historical, time-series, energy consumption data into the future. This works best for short-term forecast up to 5 years or so.

For medium-term (10-15 years) forecasts, it is considered more appropriate to correlate either per capita or total energy consumption with some aggregate parameter of economic growth such as gross national product, labor force, population, changes in price and consumer preferences, etc. For long-term (20-25 years and beyond) forecasts, it has been found necessary to incorporate additional parameters representing those changes in technology which may significantly affect the overall economic growth. Most of the forecasts reviewed were found to provide only limited information about their methodology and none provided a set of quantitative statements of the interrelationship among the correlating parameters. Some forecasts gave low, medium and high estimates, but no information was given as to the probability that the forecast values would be within the range of estimates.

<u>Some Shortcomings of Technological Forecasts</u>

All technological forecasts are believed to have a definite advantage over the earlier forecasting methodologies in which no consideration was given to anticipated changes due to the inevitable process of technological substitution. However, technological forecasts too are subject to four main shortcomings.

Firstly, there can occur the interaction of several technological developments prompted by the so-called evolutionary technology. For example, the U.S. Army decided to emphasize manned bombers rather than missiles immediately after the World War II. It did not, however, take into consideration more compact high-powered atomic weapons, advances in solid state technology, phenomenal growth of computers, development of heat-resistant materials, etc. Likewise, considerations of environmental quality now being recognized were not evident twenty years ago. Secondly, unprecedented demands of a component of a given system may completely throw the forecast off the mark. For instance, in the early 1950's it was predicted that only thirty electronic computers would be needed to handle all the calculations then being made by every book-keeper, scientist and technologist in the U.S. (66). Thirdly, the emergence of major technological developments may lead to revolutionary changes; virtually no one had anticipated discoveries such as the transistor, superconductivity, lasers, etc. Lastly, there may be a limitation imposed on technological forecasting due to the quality or inadequacy of appropriate data. It was perhaps partly because of this limitation that economists had long ignored technology as either an input to their models or assumed it to be a constant. Fortunately, in recent years government agencies, private foundations and large corporations have made an organized effort to improve the quality of forecasts by ensuring that reliable data were available.

Summary of Literature Review

Forecasting is a process that aims at visualizing future circumstances and making estimates for their needs; it is widely used in planning future policies concerned with, interalia, resource allocation. Technological forecasting is that specialized branch of the planning activity that is concerned with anticipating trends and events based on knowledge of anticipated changes in the level and spread of technology during the forecast period. It is particularly concerned with the functions of research and engineering innovation. A partial list of the various areas to which technological forecasting has been applied is shown in Appendix B.

Technological forecasts of U.S. energy requirements first appeared in the literature around 1960; about twenty-five energy forecasts have since been published. Most of these forecasts are for U.S. total energy requirements for the year 1980 and a few for the year 2000, as shown in Table I. Some forecasts have been reported for individual fuel requirements, and very few have considered fuel requirements by sectors and/or their end use. These forecasts reflect inherent differences in methodology, preferences of forecasters, time available for their preparation and the span for which they are intended. Therefore, the criterion of accuracy, per se, should be viewed only in a relative setting. Rigorously speaking, the criterion of a technological energy forecast being reasonable rather than accurate seems more appropriate.

Almost all the forecasts discussed herein were prepared before the recent surge of public and governmental concern about the environmental quality. Therefore, they contain little, if any, information about the effects of environmental quality control legislation on future energy consumption patterns because the production, transportation and utilization of energy is deeply involved with environmental quality and conservation considerations.

There has been observed a definite relationship between U.S. total energy consumption and gross national product (in constant dollars) (67) over the past 150 years. This relationship has also shown that a decreasing amount of energy has been required for each unit of GNP (9); however, the trend appears to be changing, and in the future, it is possible that a constant or even increasing amount of energy per unit of

GNP may be required if the currently accelerated rates of energy consumption continue. One reason for this changing trend is that the technical efficiency of new electric power plants and other energy conversion devices is no longer increasing substantially and may even decrease over the next several decades.[5] Most of the forecasts reviewed herein did not consider any such structural changes in the U.S. energy-economy system.

In the case of individual energy sources (fuels), most of the forecasts made several convenient but questionable assumptions. A major and common assumption is that the overall and relative prices for various energy sources will remain such that their prices need not be explicitly considered. A second and related assumption is that there will be no limit on the availability of any energy source. This assumption of unlimited availability or fuel at no change in their relative prices is of questionable validity as has been recently evidence in the wake of U.S. energy crisis (68) in general and shortages in the supplies of natural gas in particular.

Another significant observation that should be made before concluding this chapter is concerned with the absence of an analytical framework for the forecasts reviewed herein; nearly all have been based on qualitative, intuitive judgements or simple extrapolations with respect to time. Only four forecasts (8 ,9 ,10 ,53) which did incorporate some analytical tools could be identified, but these, too, were limited to using either linear or multiple regression statistical

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[5]This does not necessarily mean that the U.S. economic efficiency is decreasing. Technical efficiency must be distinguished from economic efficiency.

techniques. That partly explains the reason why there are hardly any mathematical formulations in this literature review. In fact, the above observation concerning the absence of an analytical framework for nearly all U.S. energy forecasts was recognized quite early in the course of this study.

The need for developing an energy forecasting methodology based on a theoretical and analytical framework is self-evident; hence, the justification for developing a numerical techno-economic energy model for forecasting U.S. total energy requirements for the years 1980, 1990, 2000 and 2025.

CHAPTER III

BACKGROUND FOR THE MODEL

All technological forecast models contain certain basic elements representing those parameters which, in the opinion of the forecasters, influence the models' behavior. In case of technological energy forecasting, the parameters which are believed to influence the forecasts are generally considered in terms of some aggregate technological and economic parameters. Only those parameters which are believed to evolve fairly consistently over a long period of time are actually incorporated in the formulation of technological energy forecasting models. However, the question of selecting an appropriate set of parameters poses considerable difficulty and introduces a degree of uncertainty in all energy forecasts. On the basis of the literature review presented in the preceding chapter, it was concluded that nearly all technological energy forecasts were made by correlating historical time-series energy consumption data with some aggregate economic parameter such as population growth, gross national product, per capita income, changes in labor force and level and spread of technology, etc.

For a systematic study of the background of the techno-economic model representing the U.S. energy economy, the following discussion is divided into four sections. The first deals with the very nature of the energy forecasting problem. The second discusses a conceptual framework emphasizing the role of energy as an under-grid for all terrestrial activities, and the third and fourth sections describe the economic and technological settings of the model respectively.

Nature of the Energy Forecasting Problem

It is well known that individual techno-economic systems, like the one under study herein, tend to grow in size and complexity. Since the problem at hand lies at the interface of economics and engineering, it seems necessary to identify and quantify the interrelationships among those economic and technological parameters which affect the U.S. energy-economy system. In such systems, elements of complexity arising from the interaction of technological and economic forces become an integral part of the nature of the problem itself.

Since the accuracy of energy forecasts depends upon the astuteness with which various assumptions are made by the forecaster, they may be considered, at best, contingency estimates. The element of uncertainty is an integral part of the energy forecasting problem; hence, it is impossible to make an absolutely accurate forecast. This author is of the view that the prospects for developing a fairly accurate forecasting model are greatly enhanced if the forecaster is able to systematically analyze the more specific and manageable components of the complex U.S. energy-economy system.

Energy: The Under-Grid for All Terrestrial Activities

Definition and Significance of Energy

Energy may be defined as the capacity to do work. Implicitly, however, the rate of doing work is also considered significant in this definition. It is perhaps for this reason that man has relegated horses and sailing craft to the realm of sports (at least in the developed countries) because of their limitations in rendering work at the desired rates.

Energy utilization can be traced all the way from the earliest efforts of man to the use of fire, invention of the wheel and other inventions such as power producing devices of Newcomen and Watt up to the present technological accomplishments - the computer, Saturn rocket, jumbo jet, etc. All these events have taken place within an inextricable framework consisting of Space, Time and Energy; these may be characterized as the three basic building blocks for the Universe. Based on this hypothesis, it seems appropriate to study energy in an institutional setting. Space and Time are believed to exist in a continuum of eternity; Energy alone lends itself to manipulation by man.

The significance of energy as an under-grid for all terrestrial activities is illustrated by the conceptual framework shown in Figure 5. It consists of four components of the physical environment: Sun, Soil, Water and Air. The sun with its radiating solar energy makes the soil fertile, causes weather conditions and accounts for an ecological balance. The above four components form a unique, indispensable and stable abode for man. Along with energy, man utilizes the three factors of production namely, land, labor and capital to satisfy all his wants. From a systems analysis view, however, the three factors - land, labor and capital - represent special cases of the manifestation of energy. Land represents a vast amount of latent chemical energy. Labor represents a stock of physical and intellectual forms of energy to exploit the other two factors. Capital represents a stock of potential

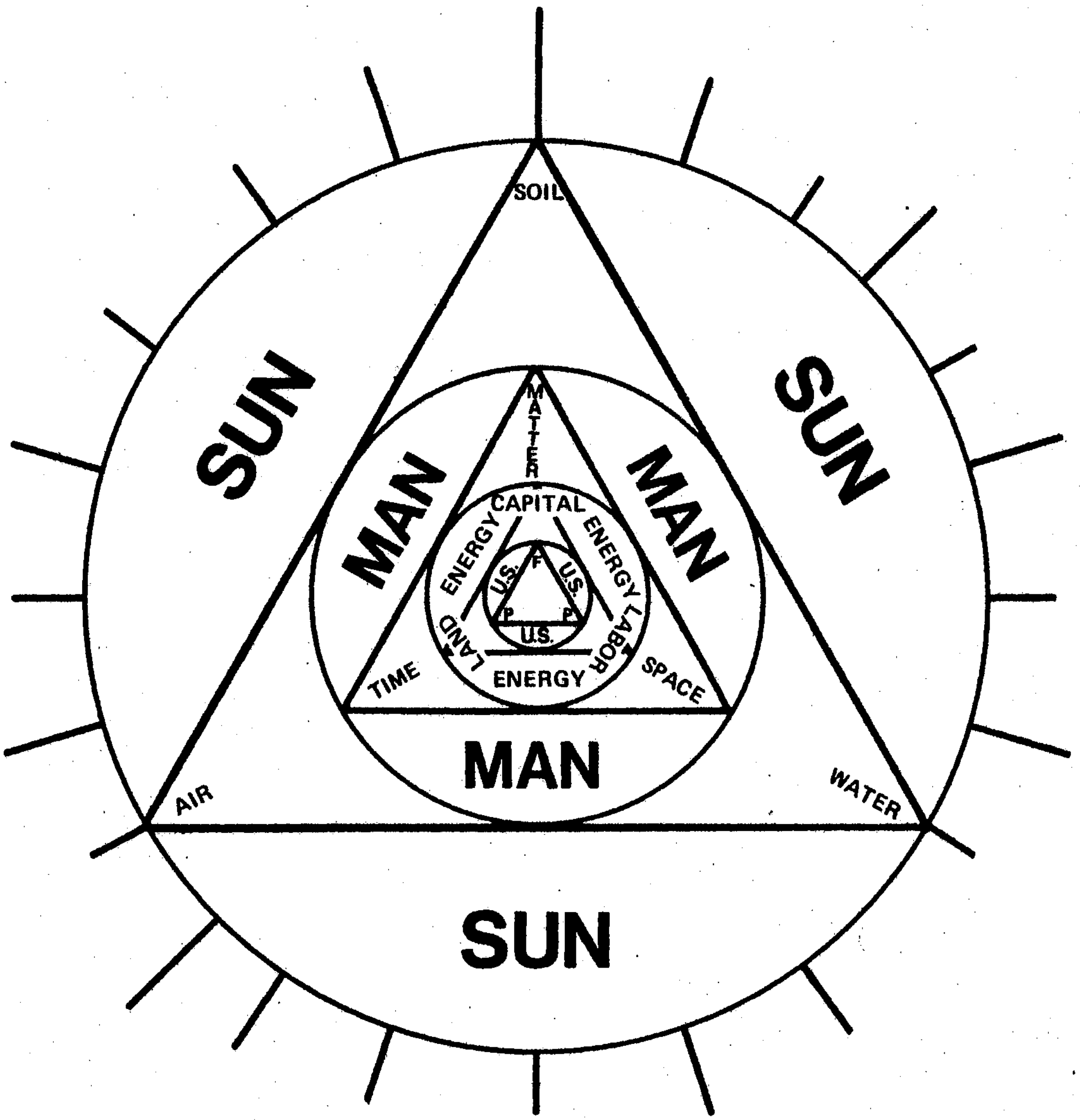

FIGURE 5. CONCEPTUAL FRAMEWORK SHOWING SIGNIFICANCE OF ENERGY AS AN UNDER-GRID FOR ALL TERRESTRIAL ACTIVITIES

Note:
The letters P, P, F in the smallest triangle denote past, present and future respectively.

form of energy. Energy, therefore, plays a significant role in the production of goods and services - a central concept in economics.

The Concept of Energy in Economics

From a historical perspective, the sweep of economic concepts from the early Physiocratism to early Classicism in the 18th Century and its extension into the 19th Century, may be regarded as improvements in the theoretical edifice of economics. The main contribution of Adam Smith (69) was to free economic theory from the shadows of ethics that the Physiocrats like Quesnay had cast upon it and, to substitute concepts dealing with the relationships between price, utility and labor. Then came Walras, Jevons, Menger and Marshall who made significant contributions to pure economic theory. It was not until 1936 that Keynes enunicated the principles of the so-called Keynesian economics dealing with the theory of output as a whole. Then the idea of simulating an economy with mathematical models, based on aggregate economic parameters, took firm roots; Samuelson (70), Tinbergen (71) and others have successfully shown the merits of economic modeling in the past three decades or so.

The school of Physiocratism, which flourished in France, considered economics in terms of land being the primary source of wealth (*les richesses*). The economists of the classical period regarded labor instead, as the primary factor of production. In retrospect, it seems that both schools of thought had grasped the essence of economic activity - the energy. The Physiocrats being in an agricultural country at that time were prone to consider economics largely in terms of land, and the Early and Late Classical Economists being amidst the industrial revolution, attached more importance to labor. Both groups, however, considered wealth in terms of stock and flow. Thus the mechanism of economic activity was fully realized nearly two hundred years ago, whereas the law of conservation of energy had not then been formulated. In fact, the current concepts of energy *per se* had not even entered into human thinking.

From a broad techno-economic stand point, energy[6] may be regarded as the common denominator of all means of production. Adam Smith published his celebrated work, "The Wealth of Nations," in 1776, in which he discussed labor of every nation "... as the fund which originally supplies it with all the necessaries and conveniences of life which it annually consumes."(69) Economists like Carver (72), Pigou (73) and Pickler (74), during the first quarter of this century, attempted to relate the cycle of human production and consumption in terms of energy in an agricultural context.

Based on the foregoing remarks, the relationship of energy with other techno-economic factors of production is illustrated in Figure 6.

The Concept of Energy in Engineering and Technology

The essential link between energy and work has always been an engine or some sort of an energy conversion device. For example, the human body, Watt's steam engine, the internal combustion engine and the turbines of today - all these represent energy conversion devices producing work with varying degrees of efficiency. In fact, the

[6] In this context it is to be appreciated that all the economic factors of production embody energy either directly (e.g. as fossil fuels) or indirectly (e.g. land, labor, capital, knowledge, etc.).

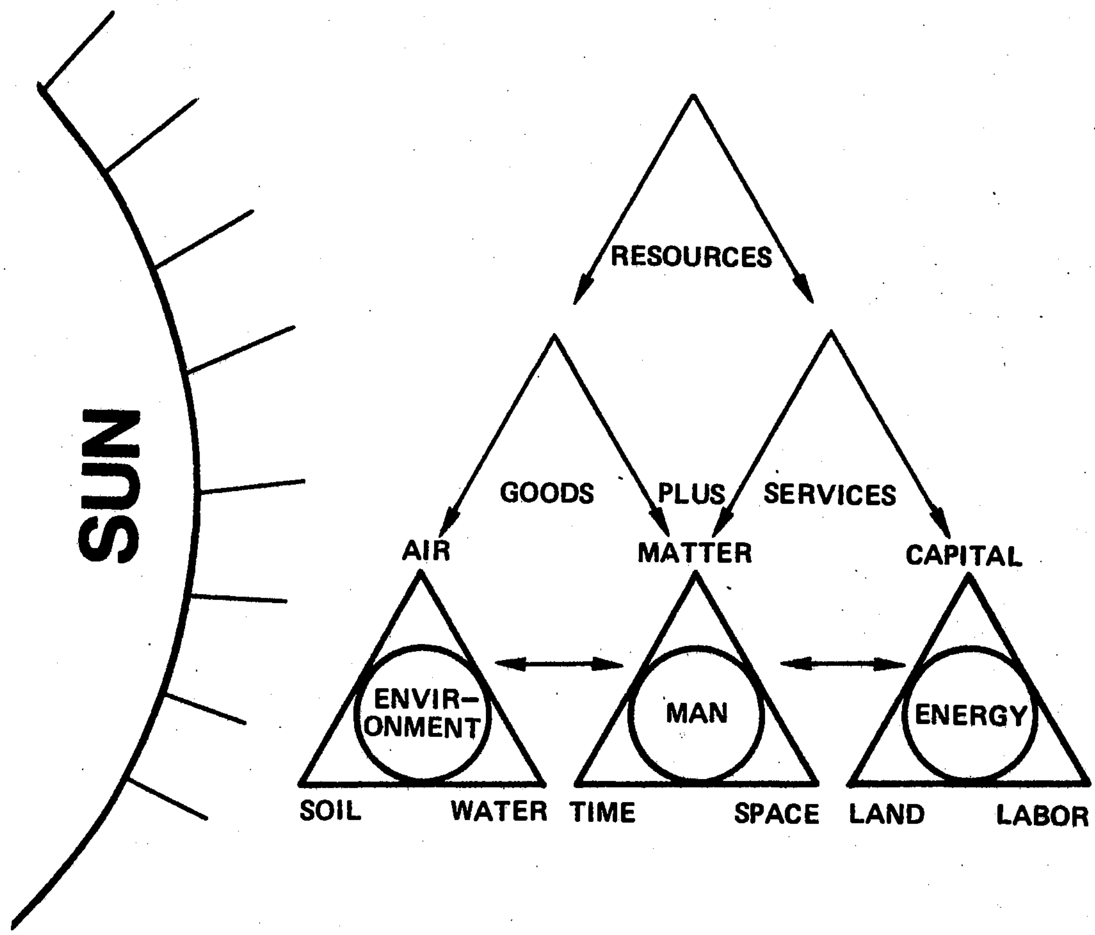

FIGURE 6. RELATIONSHIP OF ENERGY WITH OTHER TECHNO-ECONOMIC FACTORS OF PRODUCTION

development of various types of engines has proceeded hand in hand with the forms of energy available for utilization.

Engineering and technology are meaningless without an adequate energy base. Energy has served as the common fulcrum around which the levers for technological and economic development have been applied. Like a hugh grid, energy encompasses all branches of engineering activity. Even the term "engineering" is a legacy from the times of James Watt who developed the steam engine two hundred years ago. This author is of the opinion that the practice of "engine-ering" has far exceeded its originally envisaged scope; and, it may well be reworded as <u>energeering</u> for it is in the discovery, development, availability, allocation and utilization of energy that all of the terrestrial activities can be analyzed today. In a sense, engineering is the consequence of energeering.

In short, energy is a common denominator of all the activities 'under the sun'; without it, only a state of inertia will prevail. It serves as a gigantic scaffold supporting the vast structure of the world in action.

Economic Setting of the Model

The significance of energy in sustaining the U.S. economy is considered axiomatic. Since it serves as an essential factor of production, the proposed energy forecasting model has to be formulated in terms of several economic and technological parameters characterizing the U.S. economy. This section, therefore, covers a discussion of the past growth of the U.S. economy and its future potential.

Review of U.S. Economic Growth

The U.S. economic achievements have been accomplished in an environment favored by geographical, historical and political circumstances over the past century and a half. These circumstances have been characterized by several distinct changes. Firstly, the population increased by over 30 times during the period 1800-1970. There has also been a westward shift in population. Secondly, dramatic changes have occurred in the location, type and quantity of work in which the U.S. population was engaged. The Americans moved from rural to urban areas; increasingly they shifted from farming to manufacturing, trade and professional services. Lastly, the unabated increase in the total and per capita output of the economy (between 1.5 and 2 percent per year) has brought to Americans an unprecedented level of affluence.

Recent studies suggest that the great economic strides witnessed in the U.S. today can be attributed to increased output per unit of input such as land, labor, capital, energy, education, research, etc. In fact, economists now view the spectacular U.S. economic growth not simply as an increase in labor and capital supply, but very significantly as a continuing process of technological changes which, *per se*, is unthinkable without energy as an input.

Between 1854 and World War II, the U.S. economy experienced 21 recessions with varying degrees of amplitude. The great depression of the 1930's was particularly severe with unemployment reaching 25 percent of the labor force in 1933, and the gross national product (GNP) falling nearly 30 percent during the four years following the 1929 crash of the stock market (75). Prices kept on falling, factories and mines began laying off men, farm foreclosure sales were routine and nearly 28,000 banks and businesses closed their doors. Breadlines were common sights in industrial centers as nearly 5 million workers lost their jobs. To add to this misery, the summer of 1932 brought one of the most severe droughts in American history. It was not until 1937 that real GNP reached the 1929 level.

The U.S. economy in the immediate Post-War years reached a record level of production and the unemployment was at a low rate of 1.9 percent. The Employment Act of 1946 charged the Federal Government with the task of maintaining maximum employment, production and purchasing power. It marked a significant departure from the substantially Laissez faire views of the pre-war era. President Truman's 1947 Economic Report (76) outlined various economic policies and goals that called for the attainment of a four percent growth rate in real GNP and an unemployment level not to exceed 3.5 percent. But throughout 1946-48 there were increasing inflationary pressures as business investment rapidly rose from 30.6 billion in 1946 to 46 billion in 1948. The consumer price index increased 23 percent. Although the aggregate demand had increased rapidly, the scarcity of raw materials and capital quickly curtailed the real GNP growth. Thus, a series of policies to curb inflation were introduced. An increase of 20 percent in government spending was effected and several built-in stabilizers (77) were used to minimize the economic downturn.

From 1948 to 1968 the U.S. economy has been characterized by Friedman as a see-saw of inflation and recession (78). During this period, the real GNP increased at an average rate of 3.7 percent. Several years in the late 1950's were sluggish but, on the whole, the record seems impressive. During 1961-66, the U.S. GNP can be viewed in terms of seven million new jobs, doubling of business profits, increase of national (real) output by 33 percent, and the closing of the $50 billion gap between actual and potential production that plagued the American economy in 1961.

In view of the foregoing remarks, it seems appropriate to study the interrelationship of several aggregate economic parameters such as the gross national product, population, labor force, technological progress, prices, etc. Such a study of the U.S. economy, which is a vast, intricate yet comprehensible system, will facilitate the formulation of the energy forecasting model.

Economic and Technological Parameters Affecting the Model

Nearly all the aggregate parameters which affect the U.S. energy economy may be broadly divided into the following four, somewhat overlapping categories:

a) A series of demographic and social parameters interact with one another to furnish a built-in economic growth mechanism. They deal with shifts in U.S. population, labor and consumer preferences.

b) A series of those economic parameters (having political overtones) which relate changes in U.S. national economic development plans, international trade, monetary and fiscal policies, etc. More specifically, they are concerned with fluctuations in market supply and demand patterns, prices, wages, national income and expenditure, gross national product, etc.

c) A series of technological parameters affecting the technical efficiency of the U.S. economy. These are responsible for causing structural changes in the economy; for example, improvements in the technology of gas transmission and the development of automatic furnace displaced coal as a primary fuel from the U.S. energy market during the early 1940's. Such developments are responsible for the ever-changing patterns of interfuel substitution in the U.S. energy economy system.

d) Certain climatic parameters which indicate departures from the average winter and summer temperatures, shifts in patterns of precipitation, etc.

Study of Aggregate Economic Parameters

Gross National Product (GNP)

U.S. gross national product may be interpreted as the sum of either all the costs[7] or all the expenditures[8] incurred in producing the final output. It is usually defined as the total value of all the final goods and services evaluated at market prices in a given period of time. The U.S. GNP data for the past century and a half shows a pronounced, though occasionally irregular, upward trend in both total output and output per capita. However, the average rate of increase of GNP declined from 4.3 percent per year during 1850-1889 to 3.7 percent per year during 1890 -

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[7]These costs include all factor costs, indirect taxes and depreciation.

[8]These include the consumption expenditures, government expenditure and gross private investment expenditure.

1929, and to about 3 percent per year from 1930 to 1969. Such a decline is not indicated, however, by the rate of growth of output per capita which increased at about 1.65 percent per year during 1930-1969. It should be noted that this annual rate of increase has amounted to a five-fold increase in output per capita during the past century.

Total Population and Employed Labor Force

One of the most striking characteristic of the American people, from the very beginning, has been their mobility: from east to west, from farm to factory and from rural to urban areas. The primary reason for this mobility has been the absence of a feudalistic orientation, the existence of a frontier and the availability of free and equal opportunities for all.

Since the year 1800, when the U.S. was overwhelmingly a rural country, to date, the U.S. has shown a continually declining percentage of its labor force in agriculture. It declined from 80 percent in the year 1800 to about 9 percent in 1969. The labor force released due to this has found outlets in other sectors, notably manufacturing and construction. From a share of about 20 percent in 1860, these two sectors employed over 33 percent of the total labor force in 1950. Although there have been shifts in labor working in various sectors, the labor participation rate has remained within a very narrow range. For example, from 1890 when this rate was about 42.2 percent, it has increased to about 46 percent, averaging around 43.8 percent. This circumstance reflects stability of the male working group aged 25 to 64, a marked decline in labor force participation for younger and older people and an increase in the proportion of women seeking jobs.

The term labor force was originally used by the National Industrial Conference Board during the 1930's as synonymous with the total number of gainful workers. Kuvin (79) is of the following view:

> The labor force, viewed as a reserve of potential workers having gainful occupations, must of necessity have an inertia with respect to its size and growth. That's to say, the number of available persons on call plus the number engaged in remunerative pursuits does not fluctuate with business swings. Each year there is an outflow of workers from the force through emigration, death, retirement, physical disability and the like, but there is also an inflow through immigration, increased age of young people, termination of education, increasing remunerative occupations for women, and so forth. Underlying these flows in and out of the labor force are such basic factors as a changed standard of living, increased mechanization, population, age composition and growth.

With this definition, the idea was abandoned that the labor force was a slowly changing body of workers responsive chiefly to changes in population. Instead, the flexibility of the working population was clearly demonstrated because, the amount of movement into and out of the labor force from week to week or year to year, the potential increase or decrease due to the changing military environment of the country and the characteristic of persons entering or withdrawing in response to variations of aggregate demand were clearly shown by the monthly statistics or labor force.

Bancroft (80) is of the view that the term labor force used as a measure of the current labor supply has some defects. It is not a measure of total labor supply except in the sense of the number of workers who are or could be engaged immediately. This concept gives a minimum measurement of individuals available immediately amongst the labor supply. Several sources of discrepency in classifying labor force data - affecting unemployment and hence labor force participation rates -

have been discussed by Bowen and Finegan (81). However, it should be remarked that such difficulties do not become a source of serious error if consistency in the interpretation and use of labor force data is maintained.

Technological Change

Technological change refers to any change in the amount of the factors of production required per one unit of output. This is a broad concept encompassing shifts in product mix, substitution effects, non-linear input requirements, economies of scale as well as shifts from one production function to another. Technological changes may be considered synonymous with the level and spread of technology in the U.S. economy.

In addition to demographic and economic factors, technological developments in the U.S. have had significant contribution in reducing the overall energy requirements per unit of GNP produced. Strout (53) has estimated that, if the U.S. economy had continued in 1954 with the level and spread of the 1939 technology, it would have required an additional input of about 9.3×10^{15} BTU or 24 percent of the total energy demand in 1954. This saving was affected as the composite result of improvements in technical plant efficiency, energy conversion techniques and, in many cases, the substitution of capital equipment for energy as a factor of production.

Underlying the migration of labor from primary occupations through secondary to the tertiary ones, there lies the impelling force of technology. The U.S. agriculture presents a noteworthy example in which the use of technology has considerably enhanced productivity. Between 1880 and 1968, for instance, the time required to harvest one acre of wheat on the Great Plains has fallen from twenty-two hours to two. Meanwhile, the time needed to raise 100 bushels of corn dropped from 147 man-hours in 1910 to four or five man-hours at present (82). To meet the rising demands for goods and services, the average output per worker per hour has steadily increased in response to increased technical knowledge, research and mechanization.

The increase in labor productivity for the goods sector of the economy has been greater than for the services sector. The reason for this circumstance is that hugh capital expenditures have been invested in the form of new plant equipment. Such expenditures at least in the short run tend to be irreversible because equipment, once installed, becomes available for use. Therefore, it is generally agreed that capital investment and productivity have a positive correlation; technology stimulates investment, which in turn, promotes new advances in technology.

Price-Cost Mechanism

The so-called Fisher's equation of exchange (83) relates the quantity of money available in an economy to an average level of price. In its simplest form, the equation is given as:

$$M\,V = P\,T$$

where,

M = quantity of money available in an economy.

V = velocity of circulation or the number of times that an average dollar is spent per unit of time.

P = the general level of price or a price index.

T = the number of transactions made in an economy per unit of time; this is a measure of physical output.

The above equation states that the amount of expenditure (M times V) must equal the amount of receipts (P times T). This equation does not, however, give a causal relationship between M and P. The subject of supply of money in the U.S. economy has been exhaustively covered under the crusading enthusiasm of Friedman (84).

From a macro-economic point of view, the effect of more money or more spending on prices cannot be determined unless we also take into account its effect on the volume of transactions or gross output. For instance, if there is increased spending in the U.S. economy, either by the government or the private sector, these expenditures will have multiplier-mechanism effects spreading throughout the economy. The result will be increased output and employment, provided it is possible to raise the output. However, there may be exceptions, too; for example, during 1934-40 when output increased by 50 percent, the prices rose by less than five percent only. This was due to the great amount of unemployed resources, making it easy to expand output without price increases. But this may no longer be true when a level of high employment or nearly full plant utilization is already reached. Then an increase in spending can not quickly lead to an increase in output simply because the resources for more production are lacking. The result, instead, will be an increase in prices. Therefore, there should be considered a corollary to the above statement; additional spending from any source is inflationary when it is difficult to raise output.

The U.S. Economy: Quo Vadis?

In view of the foregoing two sections, it seems appropriate to take a look at the long-term prospects of the U.S. economy. This seems particularly relevant to the objective of this study because the anticipated changes in the patterns of the U.S. economic growth will also affect the energy forecasting model.

President Nixon in his 1970 State of the Union message told the U.S. Congress,

> Our gross national product will increase by 500 billion dollars in the next 10 years. This increase alone is greater than the entire growth of the American economy from 1790 to 1950. The critical question is not whether we will grow, but how we will use that growth.

The tendency to take long-term U.S. economic growth for granted is a by-product of the superboom of the 1960's, the longest period of uninterrupted economic growth. Prodigality has been the motto of the U.S. economy during the past decade. Recent forecasts by the U.S. Bureau of Labor Statistics, the Council of Economic Advisors, National Industrial Conference Board, the National Planning Association and many other governmental and private organizations have strengthened the optimism for continued U.S. economic growth.

Between 1959 and 1969, real gross national product of the U.S. increased at an average of 4.3 percent a year. For the future, the most optimistic forecast is continuation of the trend at 4.3 percent per year, whereas the most pessimistic one projects growth at 3.5 percent. However, current trend in GNP growth may be entirely misplaced in view of recent departures of productivity and labor force from their long-term trends. Since 1966, for instance, productivity growth in the private sectors of the U.S. economy has averaged only about 1.6 percent instead of the expected 3 or 3.2 percent. The labor force, on the other hand, has increased by more than 2 percent a year since 1965, about 33 percent more than its long-term trend.

Silberman (85) has discussed the factors responsible for the departure of several key economic parameters from their long-term trends. In his view, certain uncertainties relating to political, social, cultural, demographic and technological changes may have affected the rates of growth of U.S. productivity and labor force. If, for example, productivity were to regain the momentum of the early Sixties along with the current rate of increase in labor force, then the real GNP might actually grow at an average of 5.5 or even 6 percent over the next 5 to 10 years. In terms of real gross national product, this would lead to a low value of $1.1 trillion or a high value of $1.3 trillion dollars by the year 1975.

The changes in the U.S. productivity and labor force are affected by several factors. Firstly, the average number of hours worked per year, average capital-labor ratio in the economy and formulation and adoption of new social values, etc., all tend to influence both, the supply of labor force and productivity. Brzezinski (86) has postulated that the U.S. is now moving into the techne-tronic era, or a post-industrial era which offers increasing number of jobs. He believes that certain profound changes, just beginning, are creating three Americas in one. The first one has been characterized as the post-industrial America symbolized by the new complexes of learning, research and development that create unprecedented opportunities for innovation and experimentation in all sectors of U.S. economy. The second America is the industrial America symbolized by the blue and white collar workers who had seen the perils of the great depression but are now beginning to enjoy both security and leisure. The third America is the pre-industrial America of sharecroppers, migrant farm workers, miners in Appalachia, etc. In his view, a whole new Zeitgeist is in the offing.

Secondly, increased governmental intervention, particularly in view of the growing pre-occupation with the quality of life in America, is evident with respect to the allocation of resources. There are two areas which may be particularly affected by future governmental action. In view of Senator Muskie's bill requiring 50 percent reduction in auto-pollution from new cars by the year 1975, there are likely to occur several social, technological and economic changes in the overall economy. Also, there is the case of the electric power industry which has been desperately struggling to meet the rising electric power demand, nearly doubling every decade. Public concern over environmental pollution has already caused serious delays in the siting of new power plants or expansion of the existing ones (87). Delays aside, governmental action to abate pollution is most likely to increase the cost of electricity, with as-yet-indeterminate consequences for all types of consumers. DuBridge, President Nixon's former science advisor, testified last February before a Senate Committee (88):

> It may be that energy consumption is growing so fast in part because the price does not include the full cost to Society of producing and delivering it. I believe that efficient over production is just as important as ever, to our economic growth; but we delude ourselves and perhaps short-change future generations when the price of electricity does not include the cost of the damaging impact its production imposes on the air, water and land. If the total social cost of electricity or other products is included in its

price, consumers will have the inherent ability to consider the effect of their decisions on the environment.

There are additional factors which could affect the course of future U.S. economic growth. Factors such as the specter of social unrest and disorder, inability of the federal government in curbing spiraling inflation, the acceptance of a new Zeitgeist into the American way of life, or international political plays, etc. - all these have been cited by various economists, but there is no general agreement on their quantitative effects on the future of U.S. economy.

The matter of continued inflation, for example, has been studied by the Urban Institute and the Brookings Institution. Both have independently reached the conclusion that the "trade off" between unemployment and inflation is a good deal less favorable than most economists had previously thought (85). The Urban Institute Study indicated that with a four percent unemployment rate, the price level would rise by about 4.5 percent a year. It is possible, of course, that manpower training programs and computerized job banks could improve the said "trade off."

Summary of the Economic Setting

In the final analysis it seems that changes in productivity will greatly influence future U.S. economic growth. Changes in labor force, relatively speaking, can be forecast much more accurately because of the consistency observed in labor force participation rates during the past century or so.

In the post-war period, rising productivity has accounted for two-thirds to three-quarters of the growth of GNP in the U.S. If

Brzezinski is correct, the trend of increased productivity will continue though at a reducing rate. On the other hand, if Reich and McLuhan[9] (85) are correct, productivity may considerably decline because of a changing trend in the Zeitgeist of the younger group of U.S. population.

There is an accepted relationship between technology and productivity. According to the "wringer hypothesis" developed by the Bureau of Labor Statistics, business firms usually do not realize the full benefits of new or improved technology until they have been forced to go through the wringer, a process that leads them to cut costs and work at productivity gains. But there also exists an element of concern that some major sectors of the U.S. economy, such as the utilities and petroleum refining sectors, may have already exhausted the gains accruing from old technologies. In case of electric and gas utilities, for example, output per man-hour increased at an average rate of about 6.2 percent a year during 1947-1965; since then, however, the rate has averaged about 4.1 percent. The problem is not so much that utilities can no longer realize economies of scale, but that concentrating output in fewer but bigger generators endangers hugh productivity losses even if only one such unit goes out of commission (89).

The rapid expansion of antipollution measures has also raised further questions about productivity. Since the current price system does not reflect the social costs of pollution, any significant attempts to abate pollution would require inputs of capital and labor that will not be reflected in any increase in input. By definition, therefore, antipollution measures will tend to lower productivity. There may be

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[9] They contend that a large proportion of the increase in future labor force will occur in the younger age group (18 - 30 years).

other indirect consequences as well. The effect of imposing stringent regulations on the electric power and automobile industries - which are major sources of pollution - would also result in decreased productivities because the manufacturing and the transportation sectors of the economy are highly energy intensive.

In view of the foregoing remarks, it seems appropriate to study the future total energy requirements for the U.S. in relation to the composite effect of at least the following aggregate economic indicators: gross national product, population, labor force, productivity as reflected by technological change and price of energy.

Technological Setting of the Model

The study of the U.S. economy has been traditionally ascribed to economists who have published most of the energy forecasts so far. Their methodology has been either to project the historical, time series energy consumption data into the future or to use the so-called building-block approach. If forecasts of each major energy sources or use are made and added together for the total energy projection, the forecast is classified as a building-block approach. In both cases, however, some aggregate economic parameter is correlated with some measure of energy consumption. Somewhat more sophisticated energy forecasts (8 ,9 ,53) have been based on multiple correlation and regression techniques as well.

Most energy forecasts published so far do not incorporate technology and/or price as significant parameters, although changes in these parameters can significantly affect the overall productivity of the economy. Fabricant (90) has estimated that about 90 percent of the increase in U.S. output per capita that occurred during 1871-1951, can be attributed to technological progress. The productivity gains in the case of American agricultural development is another familiar example.

Although economists have long studied various aspects of labor productivity in the U.S. economy, it seems paradoxical that none has considered labor productivity as a parameter in forecasts of U.S. energy requirements. This author recognized this limitation in the early stages of this study and felt that a parameter representing the level and spread of technology should be included in the energy forecasting model. Solow (91) has shown that the U.S. labor productivity is directly dependent upon the level and spread of technology which, in turn, may be approximated by the availability of capital per worker. Therefore, to quantify the level and spread of technology in the U.S., it was decided to analyze the availability of capital per worker versus the productivity of labor, as shown in Figure 7. By incorporating the effects of changes in technology, price and several other relevant parameters, it seems possible to study their simultaneous effect on the behavior of the proposed techno-economic model representing the U.S. energy economy system.

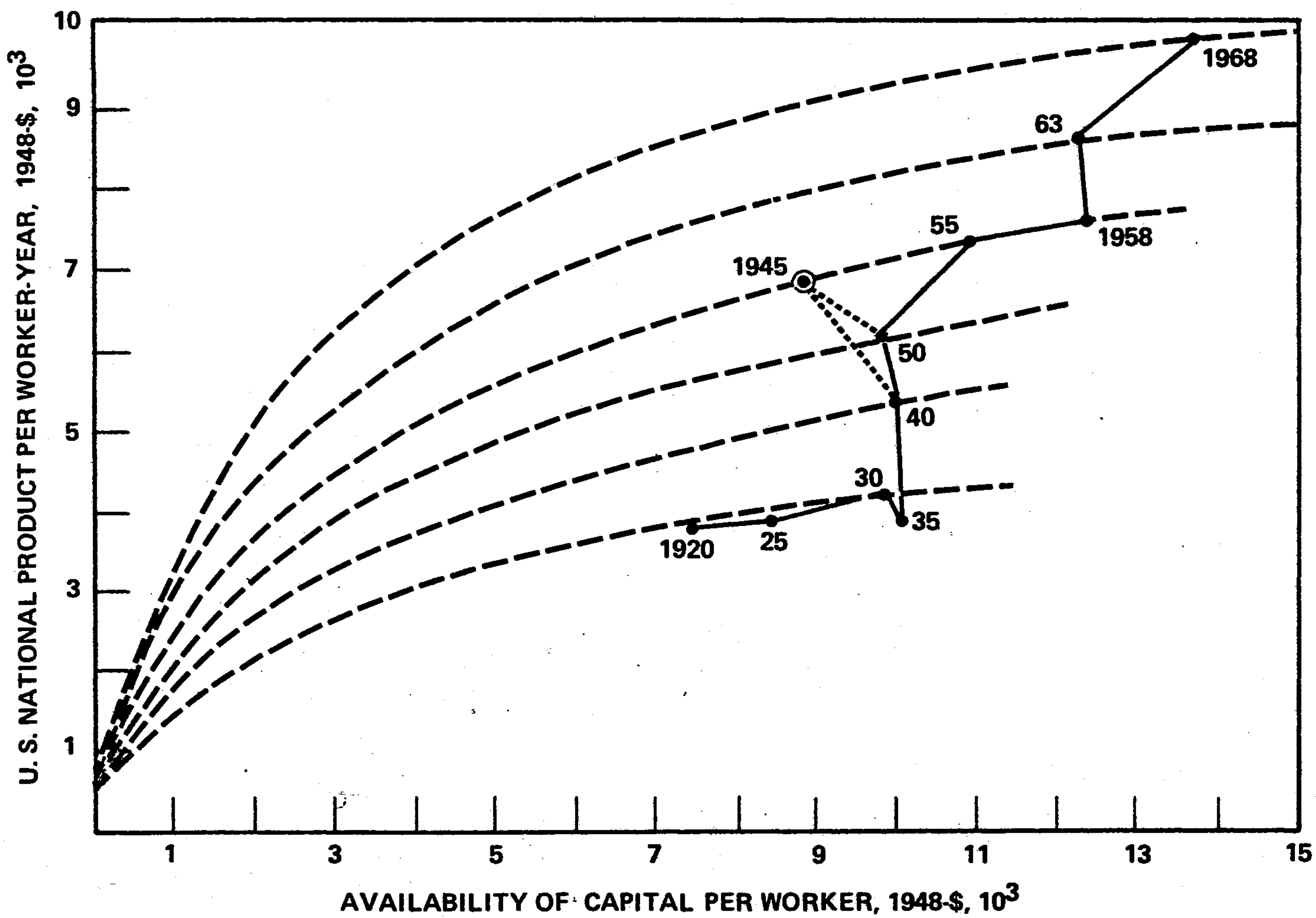

FIGURE 7. EXPONENTIAL TRENDS OF TECHNOLOGICAL PROGRESS IN THE U. S. DURING (1920–1968); AFTER TRAPEZNIKOV (18)

CHAPTER IV

METHODOLOGY

The purpose of this chapter is to describe the proposed methodology for the development of a techno-economic model representing the U.S. energy economy system. The model is to be simulated for technological energy forecasting for U.S. total energy requirements for the years 1980, 1990, 2000 and 2025. Throughout the chapter, considerable emphasis is laid on the formulation of a theoretical basis for the proposed methodology itself rather than on the accuracy of numerical results obtained from it. This has been found necessary so as to provide the model with a sound basis; its accurate quantification is then considered largely to be a function of the accuracy of the data used.

Following the statement of a generalized technological energy forecasting model, the development of the proposed techno-economic model is systematically undertaken. In so doing, the interrelationships between U.S. total energy consumption and several technological and economic parameters are analyzed. With slight modifications to the techno-economic model, a prediction-equation for U.S. total energy requirements is also derived.

Statement of Proposed Methodology

The methodology proposed for the development of the techno-economic energy forecasting model is the result of a broad engineering analysis approach in which the U.S. energy economy is considered as a system. The gross output of this system is considered in terms of U.S. gross national product (GNP) evaluated at constant (1958) dollars. From an energy balance point of view, this output requires an equivalent input which, in case of the proposed techno-economic model, is taken as the total energy input into the system.

Several components of the system affecting its behavior can be identified. The sum total of all the goods produced is consumed by the population[10] in the system; in addition, a fraction of it (denoted as the labor force) participates in the production of the GNP itself. Also, the level and spread of technology in the system determines the level of productivity, directly affecting the rate and efficiency of the production of GNP. The influence of the general price indices on the production of the GNP is self-evident.

The above model, therefore, incorporates the following aggregate economic and technological parameters: total energy consumption, population, labor force, level and spread of technology and price of energy. The quantification of this model enables a study of the simultaneous effect of the above parameters on total energy consumption.

Generalized Energy Forecasting Model

Total energy requirements for a given system are known to be a function of several parameters generally classified as economic, demographic, technological, political and climatic. Such parameters

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[10]It is realized that some of the goods produced are exported. However, from a systems point of view, energy and labor inputs are needed to produce them in the U.S. Therefore, they are considered part of the GNP and as if consumed by U.S. population.

may be called exogenous or independent parameters because they determine the energy requirements - the endegenous or dependent parameter. Therefore, the functional equation for the generalized model may be written as:

$$E = f(X_1^a,\ X_2^b,\ X_3^c,\ X_4^d,\ X_5^e,\ \ldots\ X_n^m) \qquad \text{(IV.1)}$$

where, a, b, c, ... m are suitable indices for the parameters E, X_1, X_2, X_3, ... X_n, respectively. A series of exogenous parameters represented by (X_i), which are believed to affect the total energy requirements (E) of the system are listed below:

X_1: some aggregate indicator of economic growth of the system such as: GNP, national income, etc.

X_2: a measure of the system population.

X_3: represents a measure of active population or the labor force employed.

X_4: a composite parameter of the level and spread of technology throughout the economy. This is reflected primarily through increased industrial growth and, indirectly as increased productivity of labor.

X_5: some measure of the real costs and prices in the system in general and those of the energy sources in particular.

X_6: consumer preferences, considerations of environmental quality, interfuel competition and substitution, etc.

X_7: political factors being on the formulation of public energy policy, global energy supply patterns, etc.

X_8 : considerations of imports into and exports of energy resources from the system.

X_9 : domestic energy resources supply patterns.

X_{10}: certain climatic factors indicating average temperatures during the summer and winter seasons.

It is obvious that an exact solution of equation (IV.1) is impracticable and perhaps impossible. The main difficulty arises in view of several of the X_i parameters not being quantifiable. In the past, several forecasters have circumvented this difficulty by either restricting themselves to correlating the total energy requirements parameter (E) with some measure of economic activity such as per capita GNP, or extrapolating past energy consumption trends into the future. In all such cases, however, the parameter E was correlated with no more than two of the exogenous parameters listed above.

Consideration of Design Parameters For The Proposed Model

Out of a total of seventeen aggregate economic and technological parameters, a set of six was selected for the development of the proposed model forecasting U.S. total energy requirements for the years 1980, 2000 and 2025. These six parameters are - the gross national product, population, labor force, level and spread of technology, price of energy and total energy requirements. The selection criteria for these parameters are based on considerations of practicality, availability of data and scope of this study. Although some other parameters could have been included, it was considered neither necessary nor possible to be exhaustive.

Assumptions

Like all other physical models used in engineering, the proposed model also depends, to a large extent, upon the efficacy of the following set of assumptions made; these represent a synthesis of nearly all the assumptions made for the various forecasts published so far. In some cases, however, personal judgement has been relied upon to incorporate various considerations of environmental quality and economic fluctuations.

1) Total Energy Requirements (E): This parameter is assumed to characterize the energy requirements (consumption) of all fuels used in the U.S. energy economy system. Fuels are not energy until burned and it is their energy content which is used.

2) Economic Activity (X_1): It is assumed that the U.S. (GNP) economy will continue to grow at an average annual rate, ranging from 3.5 to 5.0 percent during the forecast period. It is further assumed that the growth of the money supply determines, to a large measure, the rate of real growth of the economy (8), and possibility of a major depression is ruled out.

3) Population Increase (X_2): Starting with a rate of population increase of 1.75 percent per year in 1962, it was assumed that this rate will decrease, each passing year, by one percent of its value in the previous year. This assumption coincides with those given in Series II of the Estimates of the U.S. Bureau of Census Projection

4) Labor Force Employed (X_3): On the basis of the work by Cooper and Johnston (92), the average annual rate of

growth of U.S. labor force is assumed to vary from 1.6 to 1.7 percent. This variation is known to correlate with population growth rates in such a manner that the ratio of the U.S. labor force employed to its total population - the labor participation rate - remains nearly constant.

5) Technological Change/Rate of Industrial Growth (X_4): The Federal Reserve Board index for industrial production is assumed as a measure of the U.S. industrial growth. It is further assumed that the U.S. industrial growth is reflective of the level and spread of technology in the economy. [This is an approximation; however, it should be noted that an index measuring labor and capital productivities has also been developed, as shown in Appendix C.] It is assumed that, during the forecast period, an entirely new industry on synthetic fuels will be born. This will perhaps be initiated by coal gasification followed by oil shale utilization, use of non-polluting fuels such as hydrogen, etc.

6) Real Costs and Prices of Energy Sources (X_5): This assumption refers to fuel prices per million BTU; where data are not available, it is assumed that the average general price index for all commodities in the U.S. economy may be taken as an approximation. Furthermore, it is assumed that the fuel prices would continue to increase, at the rates evidenced during the recent past.

7) <u>Considerations of Consumer Tastes, Environmental Quality and Interfuel Competition</u> (X_6): This variable has been disregarded in the formulation of the model. However, qualitative assumptions are made in evaluating future trends of energy mix, environmental quality legislation, shifts in consumer preferences, etc.

8) <u>Political Factors</u> (X_7): Since these are generally unknown and can not be adequately quantified, it is assumed that the prevalent condition of "cold war" will persist during the forecast period. No significant change in the levels of U.S. defense spending is anticipated. The Viet-Nam conflict is assumed to end by 1973-74.

9) <u>Foreign Trade</u> (X_8): For the forecast period, there is assumed a net foreign trade in energy resources that had the same proportional relationship to domestic demand as prevailed in 1965.

10) <u>Domestic Energy Supply</u> (X_9): It is assumed that adequate energy resources will be available to meet the energy requirements for the forecast period. Variations from this circumstance may be considered in specific simulations of the model.

11) <u>Climatic Changes</u> (X_{10}): It is assumed that no significant climatic changes will occur in the U.S. during the forecast period.

<u>Elaboration of Selected Parameters</u>

Several authors (8 , 9 ,10 ,53) have studied the functional relationship between energy consumption and some appropriate aggregate economic indicators. An excellent discussion of the relationship between energy consumption and gross national product, for instance, is reported by Schurr et al (67). They have shown that during the past 50 years, a decreasing amount of energy has been required per unit of GNP in the U.S. Figure 8 shows the phenomenal increase in the U.S. total energy consumption during 1870-1970, and Figure 9a and 9b show per capita energy consumption and energy consumption per unit of GNP, respectively.

The production of goods and services by the U.S. economy requires four essential inputs namely land, labor, capital and energy which are sometimes considered in terms of aggregate economic concept called the productivity. Of the four inputs, the parameter of labor force employed (or the active population) is responsible for the production of goods and services. Those members of the population who do not contribute toward GNP can be considered, from a systems point of view, as consumers only. Therefore, total energy requirements of the U.S., when viewed as an input to the economy, should be considered with respect to both, the population and employed labor force.

From a methodological standpoint also, the so-called labor participation rates i.e. ratio of active population to the total population in case of U.S., has remained nearly constant for the past century or so. For instance, Long (93) has shown that in five years of World War II (up to April, 1945), the equivalent of 25 million full-time workers moved into civilian and military employments in the U.S. This raised the number of employed workers from 45 to 70 million, that is, to more than three for every two workers occupied in the spring of 1940. These additions enabled civilian employment to augment their strength 13 million (nearly 30 percent) while the armed forces were calling up

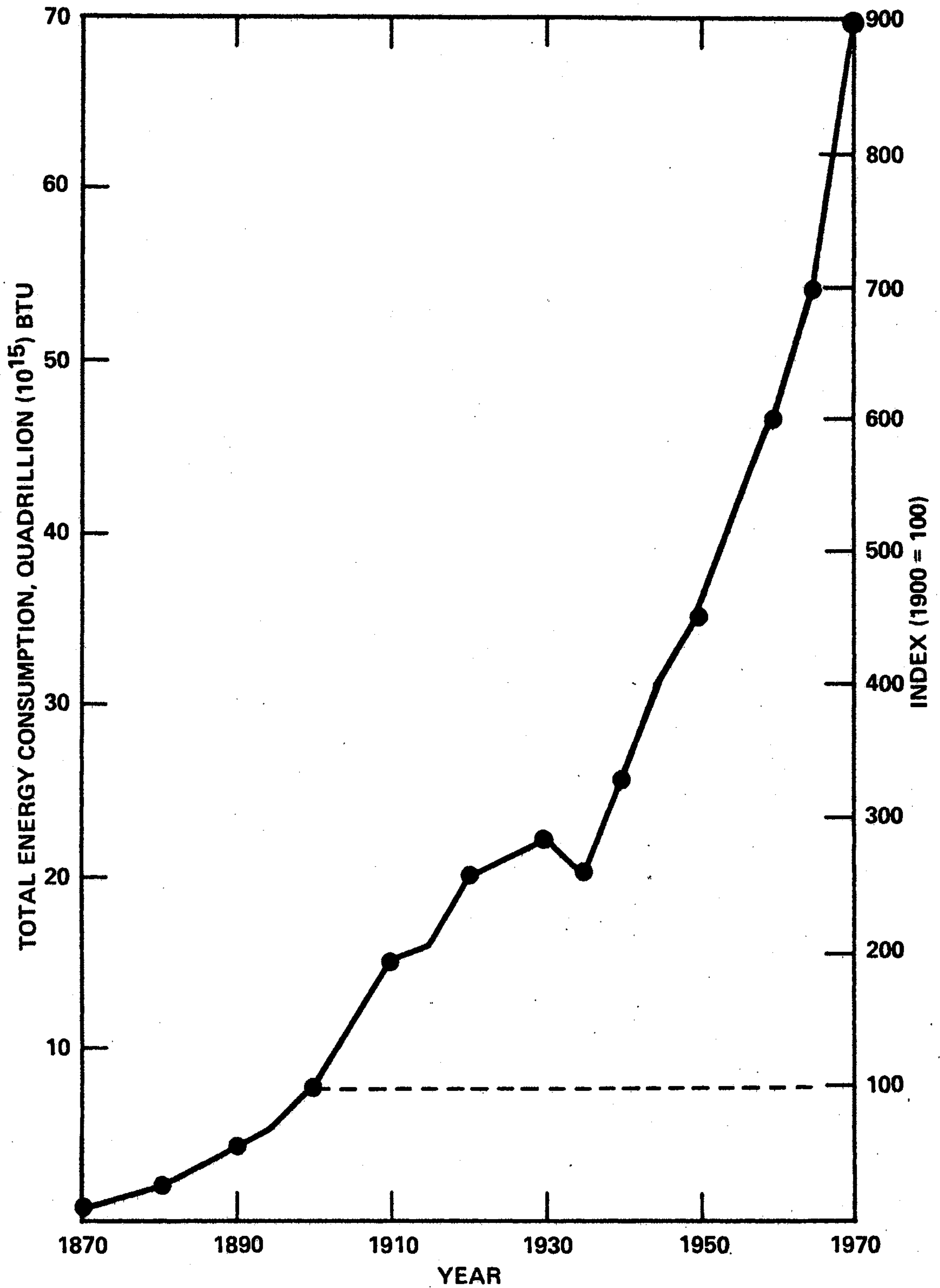

FIGURE 8. SHOWING INCREASE IN U. S. TOTAL ENERGY CONSUMPTION DURING 1870- 1970

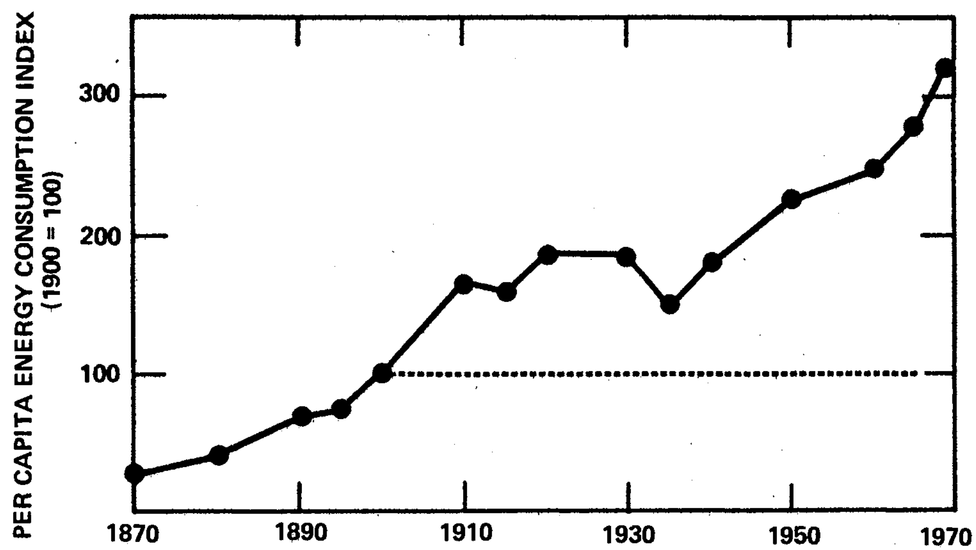

FIGURE 9a. INCREASE IN U. S. PER CAPITA ENERGY CONSUMPTION DURING 1870-1970

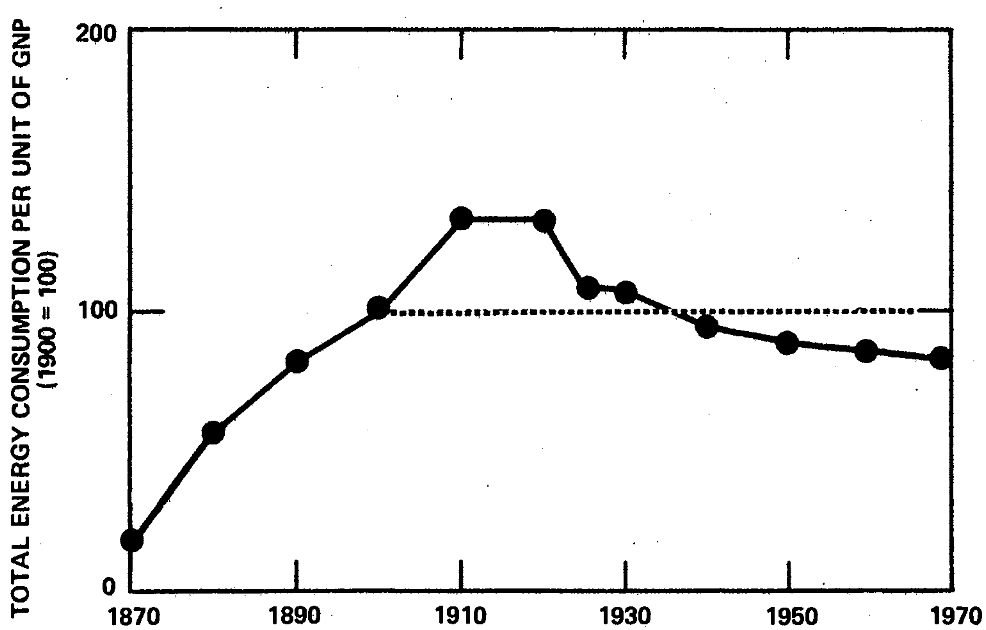

FIGURE 9b. U. S. TOTAL ENERGY CONSUMPTION PER UNIT OF GNP (IN 1958-$) DURING 1870-1970

12 million men. In an exhaustive work Bowen and Finegan (81) have shown that there is a strong positive correlation between employment and labor force participation for all major population groups. More recently, too, Cooper and Johnston (92) have shown that higher employment rates have been historically associated with higher labor force participation rates.

The fact that labor participation rates do not widely fluctuate tends to improve the prospects of forecasting, for if the long-range variation in a parameter is small, the error introduced by it is also relatively small. This is particularly relevant since Hall (94) has defined forecasting as, "... an estimate of what future observations might be if the underlying process continues as it has in the past."

In the U.S., continuous technological developments and, underlying them, a series of scientific discoveries have served as necessary conditions for high rates of growth in per capita income and productivity. The mechanization of U.S. agriculture is a case in point. The agricultural employment declined, between 1947-64, from 7.7 million to 4.4 million workers, i.e. a decline from 14 to 6.3 percent of the total civilian employment. Yet, in the said period, the total acreage in the U.S. remained unchanged at about 1.5 billion acres, and output of farm products increased. Wheat production went up 17 percent, soya beans 264 percent, rye 41 percent, barley 51 percent, maize and corn about 412 percent. The overall productivity increased 161 percent (61). These statistics also indicate, indirectly, an increase of 75 percent in available horsepower to an average farmer, 102 percent increase in the use of fertilizers and the increasing trend toward farm consolidation resulting in economies of scale. This circumstance reflects the interaction of forces of supply and demand, particularly in relation to the rising demand for labor in manufacturing and service sectors. Although the contribution of technological developments in spurring economic growth is considered axiomatic, the measurement of productivity has been a matter of considerable controversy and difficulty.

The price mechanism in an economy performs several tasks. It induces people to work and earn their incomes for living and compels consumers to restrain their demands for economic commodities. It also serves the function of coordinating the efforts of millions of organizations and individuals that constitute an economy (95). In this respect, it is merely an instrument of the society it serves; it is neither sacrosanct nor perfect. With respect to prices, two fundamentally different situations in macro-economics should be distinguished; these relate to conditions of full employment and that of underemployment. Policies that make sense in one situation may not make sense in the other. In case of an underemployed economy, for instance, increased expenditures in the public or the private sector are considered a main objective for the economic well being of its population. But increased expenditures in a fully employed economy leads, in most cases, to higher prices and not to more output or jobs (83).

In the U.S., the control of the economy is entrusted to two institutions: the Federal Reserve Board and the Federal Government. These institutions observe and analyze not only the monthly figures on percent unemployment and inflation (the consumer price index), but also many other indices to arrive at the desired mixture of fiscal and monetary control policies. Also, many economists have studied the long-term or quasi-steady state, inverse relationship between unemployment and inflation.

In the latter part of the 1950's, for instance, there was 5 to 6 percent unemployment with 1.5 to 2 percent inflation in the U.S. More recently (during 1968-69) there existed conditions of 3.5 percent unemployment with 5 to 6 percent inflation. Values of 4 percent (or less) unemployment and 2 percent inflation are believed to be reasonable and attainable under the Full Employment Act passed by the Congress in 1946. What is, in fact, attainable depends on the ratio of manufacturing to service industries and on the extent to which marginally productive workers can be improved in their skills to join the labor force. Indeed, as the service industry sector increases its contribution to the gross national product, the target values of unemployment and inflation will become more and more attainable. Figures 10, 11 and 12 show the changes in the U.S. GNP, unemployment and consumer prices, respectively, during 1959-70.

In case of the price per unit of energy, it is realized that it has an inverse relationship with energy demand. Whereas, in actual practice, such a simple relationship may not hold because of incident factors of cost-induced or market-induced changes on price, it is assumed that the price of per unit of energy varies inversely with total energy demand.

<u>Terminology of the Model</u>

The following set of symbols is used for the six parameters selected for the development of the techno-economic model:

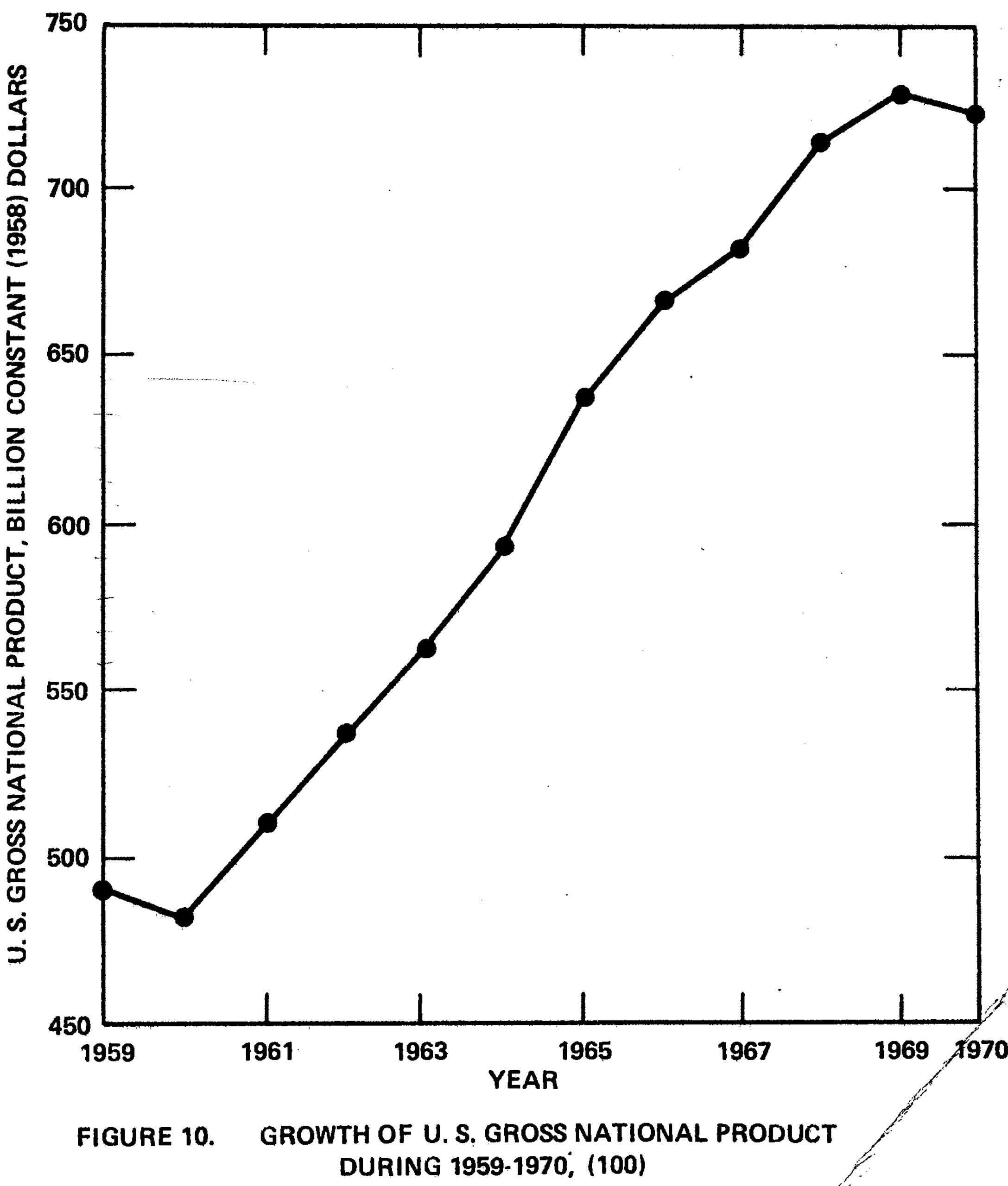

FIGURE 10. GROWTH OF U. S. GROSS NATIONAL PRODUCT DURING 1959-1970, (100)

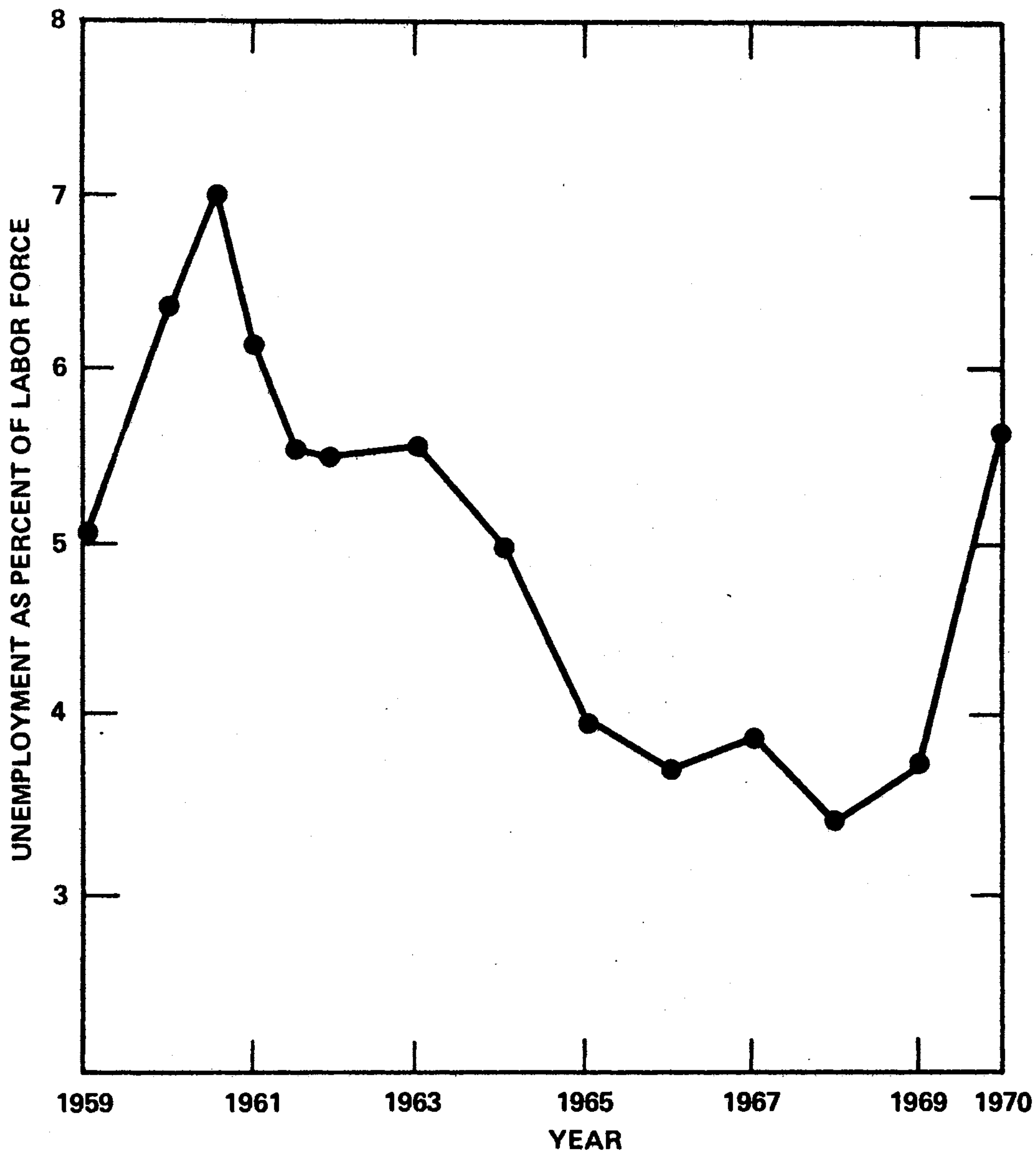

FIGURE 11. U. S. UNEMPLOYMENT SITUATION DURING 1959-1970, (100)

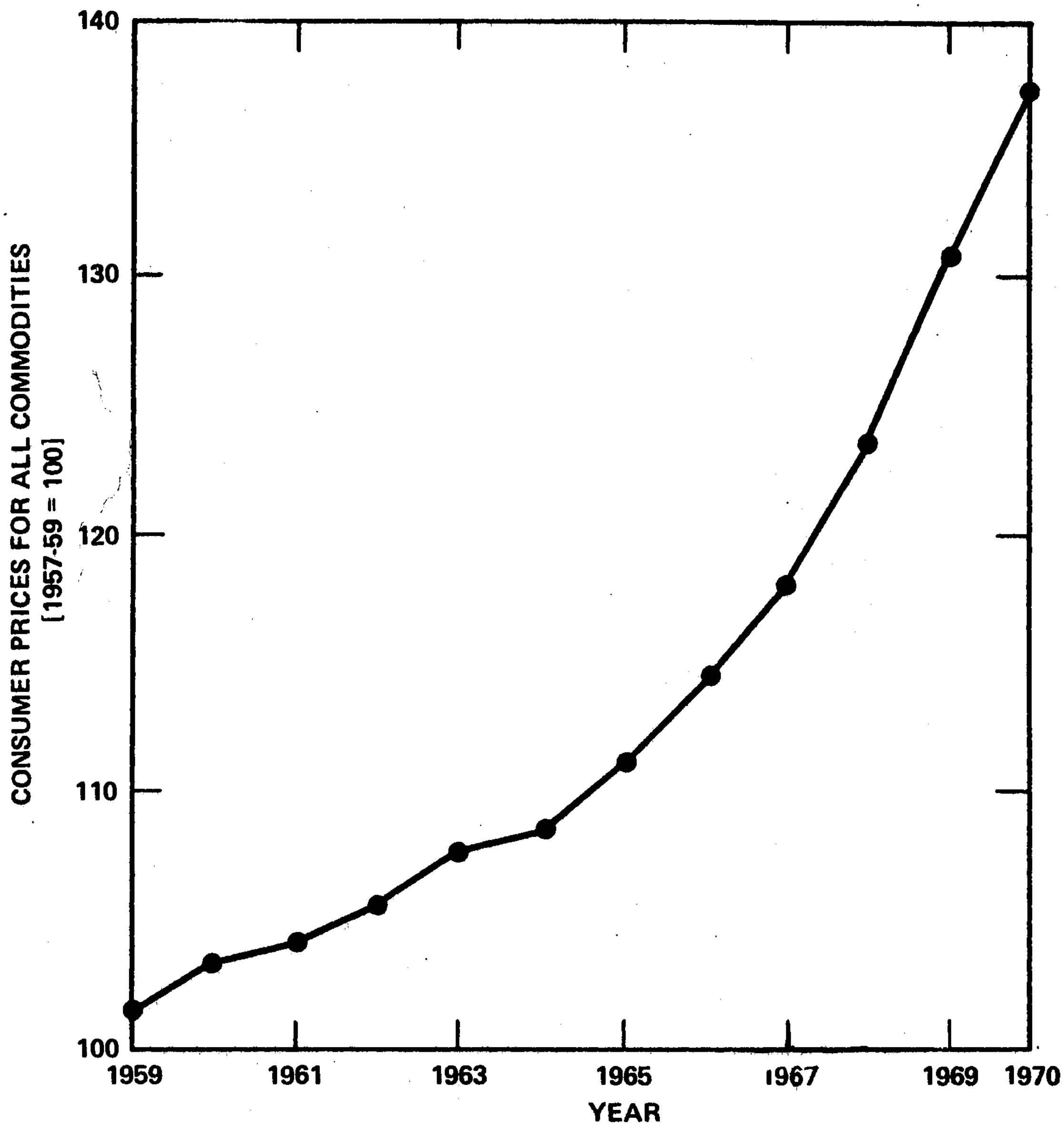

FIGURE 12. INCREASE IN U. S. CONSUMER PRICES FOR ALL COMMODITIES DURING 1959-1970, (100)

Parameter	Symbol
1) Input to the U.S. economy in terms of total energy requirements in a given year, quadrillion (10^{15}) BTU	(E)
2) Output of the U.S. economy in terms of its gross national product in a given year, billions of \$	(GNP)
3) Total U.S. population in a given year, in millions	(P)
4) Total labor force in the U.S. economy in a given year, millions of employed workers	(W)
[Labor participation rate for a given year]	$\left(\frac{W}{P}\right)$
5) A measure of the U.S. industrial production reflecting the level and spread of technology, in a given year	(τ)
6) An average index of price of energy per million BTU in \$	(ρ)

Development of the Techno-Economic Model

The major guiding assumption used in developing the proposed techno-economic forecasting model is that the process of U.S. economic growth has had several macro-economic characteristics by which the process itself can be identified and quantified with respect to U.S. total energy consumption. Furthermore, these characteristics warrant the expectation of finding a number of common aspects, interrelated in sufficiently coherent and invariant manner, to enable the projection of their composite trend into the future. Laffer (95) has constructed a macro-economic theoretical model of the U.S. economy which, he insists, is "most likely better than any of the well known larger models." He uses only raw economic data, ignores the seasonal adjustments that more conventional economists prefer, because he thinks they "smear things." He also disregards such matters as the likelihood of a steel strike next summer, the prospective size of federal deficit and the amount of savings available with the banks. In his opinion, all these things average out to zero when their effect on the overall economy is analyzed.

The extrapolation of historical time-series data is perhaps the most commonly used technique for technological energy forecasting. In general, Jantsch (46) is of the opinion that simple extrapolation of historical, time-series data for a system does have one analytical element:

> ... the intuitive expectation that the combined effect of internal and external factors which produced a trend over a past period will remain the same during a future period (deterministic technique in business forecasting) or that it will undergo an estimated graduate smooth change (symptotic technique). Studies conducted at the General Electric's TEMPO Center have shown that the factors influencing diffusion of technology complicate the picture so as to distort a smooth curve in some instances. Therefore, a basic rule for trend evaluation, in contrast to extrapolation, is to select parameters that are effected in a consistent way by the influencing factors.

Experience has shown that intuitive forecasting of scientific and technical parameters as reported by experts tends to result in linear projections. The first, and perhaps most important value of trend extrapolation may, therefore, be seen in a correction of the intuitive forecasting by giving greater weight to factors which have dominated in the past case history. In general, intuitive expert forecasting tends to be over-optimistic for the short term and too pessimistic for the long term. Some of the commonly used trend extrapolation formats are shown in Figure 13.

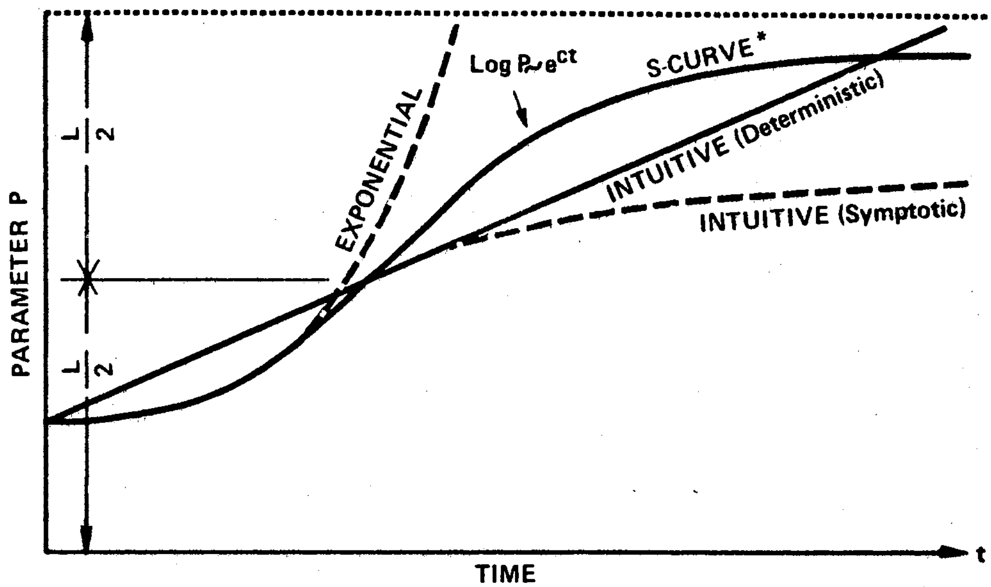

FIGURE 13. VARIOUS TYPES OF TREND EXTRAPOLATION TECHNIQUES USED FOR FORECASTING ENERGY REQUIREMENTS

*Rigorously speaking, the equation for an S-curve is given as: $P = \frac{L}{1 + ae^{-bt}}$

where, L = Upper asymptotic limit
a = Dimensionless constant
b = Constant per unit of time

It intersects the Y axis at $\frac{L}{1 + a}$.

Mathematical Formulation of the Model

In view of the interdependence of the U.S. economy and energy system, a generalized equation may be written:

$$(E) = f_1 \text{ (U.S. economy)} \tag{IV.2}$$

where, f_1 is some explicit function. Referring to equation (IV.1), it is observed that about a dozen parameters could be quantified to formulate a techno-economic model for energy forecasting. However, from the literature survey, a set of the following five exogenous parameters seemed to be of primary significance for the formulation of the model. Therefore, equation (IV.1) is modified and written as:

$$E = f(X_1, X_2, X_3, X_4, X_5) \tag{IV.3}$$

Substituting relevant techno-economic parameters in equation (IV.2),

$$\text{U.S. economy} = f_2 \text{ (GNP, P, W, } \tau, \rho) \tag{IV.4}$$

and, combining it with equation (IV.3):

$$(E) = f_1 \left[f_2 \text{ (GNP, P, W, } \tau, \rho) \right] \tag{IV.5}$$

$$(E) = f_3 \text{ (GNP, P, W, } \tau, \rho) \tag{IV.6}$$

The interrelationships among the above six techno-economic parameters were analyzed and plotted using the IBM 360, model 365 computer and the cal-comp plotter #565, respectively. From an extensive parametric analysis described in Appendix D, the following set of relationships may be written:

$$
\begin{aligned}
(E) &\propto (P) && \text{Total population} \\
&\propto (GNP) && \text{Gross National Product} \\
&\propto (\tau) && \text{Industrial production index;} \\
& && \text{proxy for the level and} \\
& && \text{spread for technology} \\
&\propto \left(\frac{1}{W}\right) && \text{Employed labor force} \\
&\propto \left(\frac{1}{\rho}\right) && \text{Some measure of aggregate} \\
& && \text{price index}
\end{aligned}
\tag{IV.7}
$$

Therefore, Equation (IV.6) may be written as:

$$\left[\frac{(E)}{(P)} = f_4\left(\frac{GNP}{W}, \tau, \frac{1}{\rho}\right)\right] \tag{IV.8}$$

or,

$$f_5\left(\frac{E}{P}, \frac{GNP}{W}, \tau, \frac{1}{\rho}\right) = 0 \tag{IV.9}$$

where, f_5 is an implicit function.

Vogely and Morrison (9) and Strout (53) have considered their energy forecasting models as logarithmic linear or exponential functions. However, their models did not incorporate any of the three parameters – (W), (τ) and (ρ). In order to quantify the model represented by equation (IV.9), several plots were made to study the functional relationship between the three groupings – $\left(\frac{E}{P}\right)$, $\left(\frac{GNP}{W}\right)$, $\left(\frac{\tau}{\rho}\right)$ – of the six parameters. Figure 14 shows the data (from 1915–1968)[11] pertaining to the two groupings – $\left(\frac{GNP}{W}\right)_{1958}$ and $\left(\frac{E}{P}\right)$; the (GNP) is normalized with respect to the number of workers employed (W), and

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[11] To ascertain the validity of Figure 14 over a longer span of time, the data point for the year 1900 is also included.

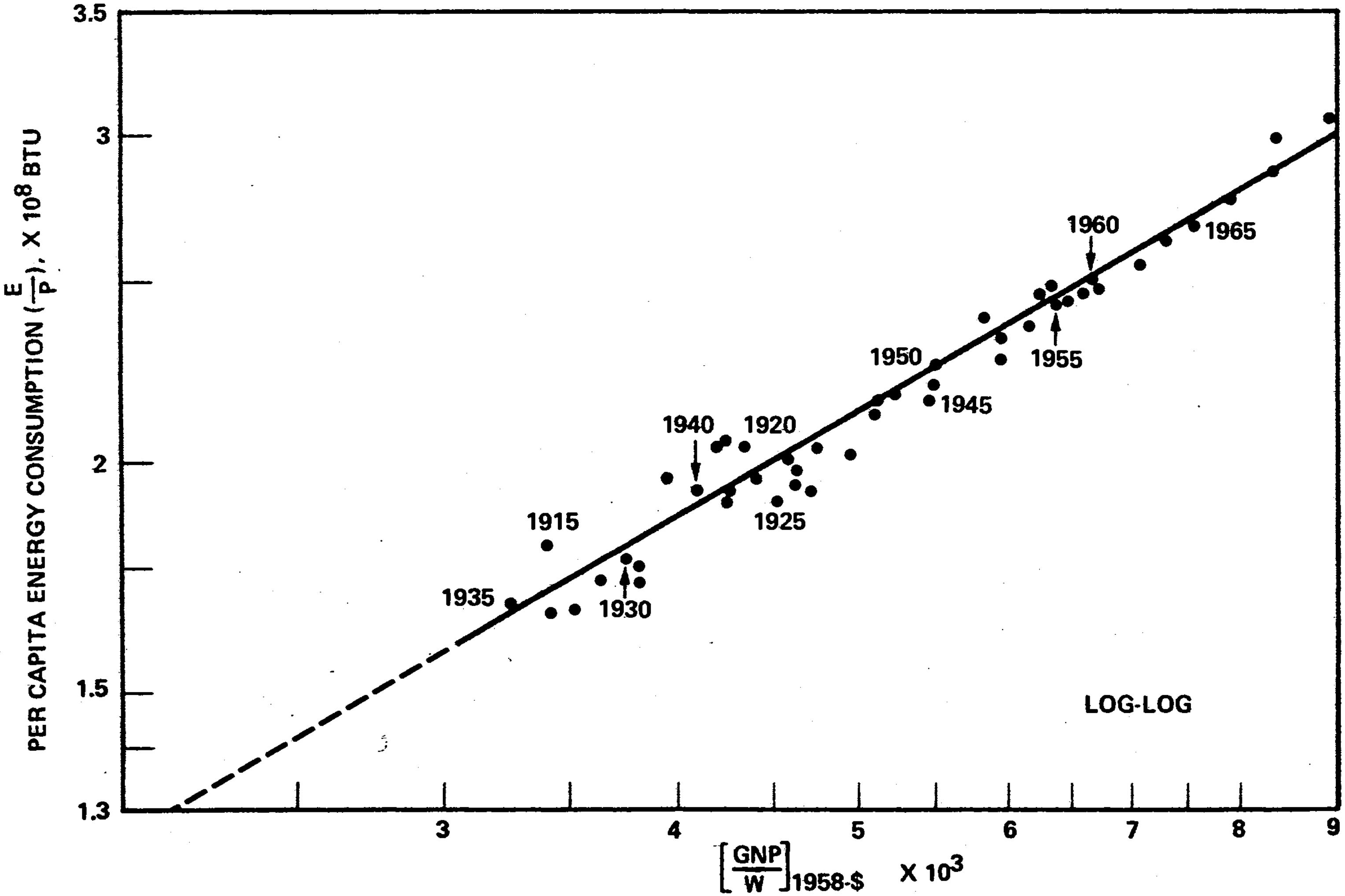

FIGURE 14. RELATIONSHIP BETWEEN $\left[\frac{E}{P}\right]$ and $\left[\frac{GNP}{W}\right]$ DATA (1915-1968), EQUATION (IV. 9)

U.S. total energy consumption is normalized with respect to total population. Figure 15 shows the plot between $\left(\frac{\tau}{\rho}\right)$ and $\left(\frac{E}{P}\right)$. A composite log-log-log plot of all three groupings representing the proposed techno-economic model is shown in Figure 16.

Variations of the Model

Six versions of the proposed techno-economic model given by equation (IV.9), are considered by varying three parameters namely - gross national product (GNP), level and spread of technology (τ) and price index (ρ). When an attempt is made to quantify these parameters exactly (as in the case with E, P, and W), several methodological difficulties are faced. Particularly in case of the parameter (τ), no exact method for its quantification is available. However, it is observed that (τ) may be closely approximated with the Industrial Production Index published by the Federal Reserve Board. Also, three variations for the price parameter (ρ) are considered. In view of the foregoing remarks, the following set of six versions of the proposed model is further analyzed by plotting the parameter (E) against relevant groupings of the other five parameters.[12]

<u>Model Version 1</u>

$$E = k \cdot [\mathrm{GNP}]_{1958\ \$} \cdot \left[\frac{P}{W}\right] \cdot \frac{\left[\begin{array}{c}\text{F. R. B. Industrial}\\ \text{Production Index}\end{array}\right]_{1958}}{\left[\begin{array}{c}\text{Wholesale Price Index}\\ \text{for all Commodities}\end{array}\right]_{1958}} \qquad \text{(IV.10)}$$

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[12] The six equations (IV.10) to (IV.15) are not dimensionally homogeneous; however, the dimensional homogeneity of the equation (IV.9) is shown in Appendix V. For correlation purposes, this criterion is not considered significant.

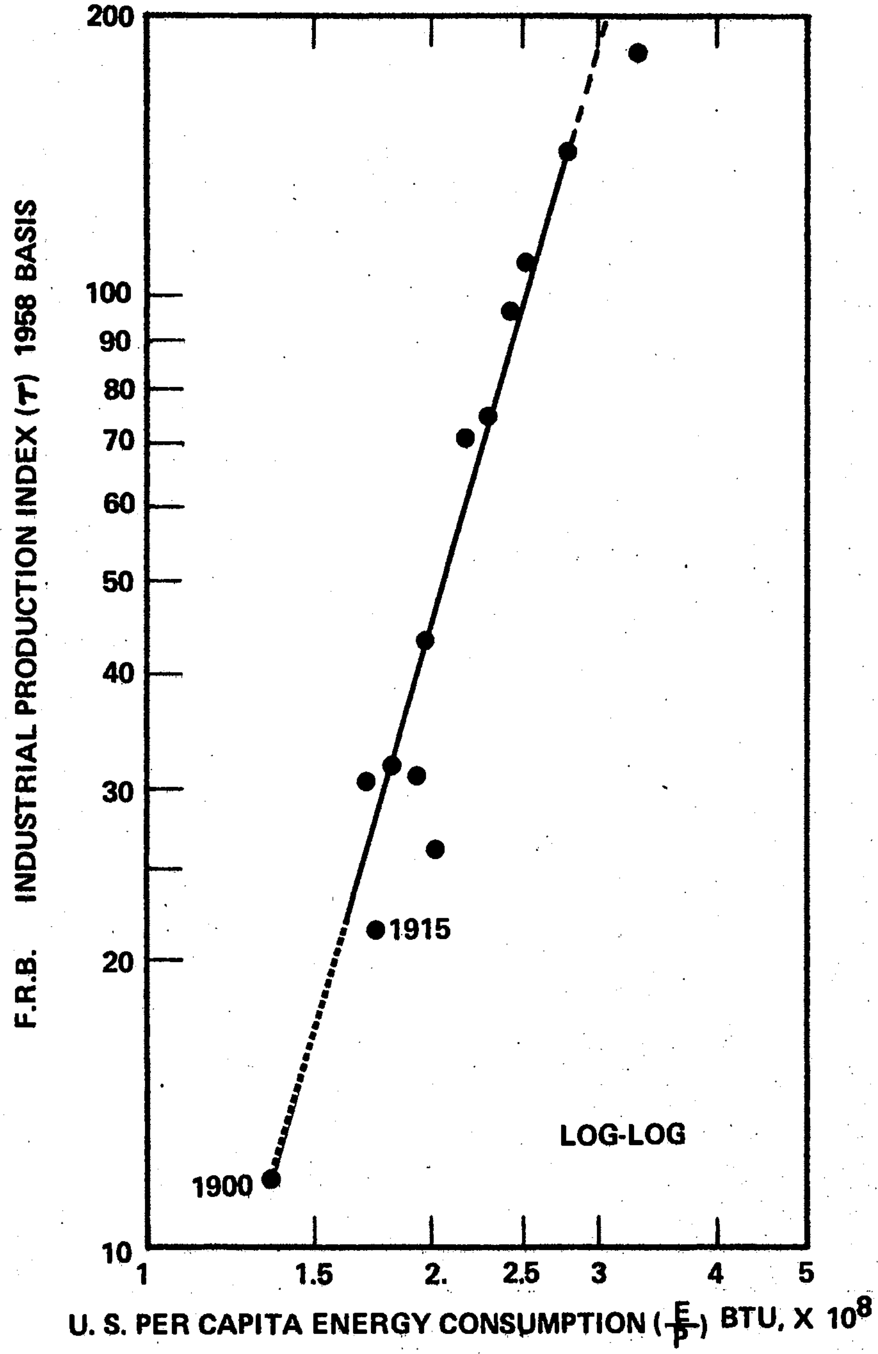

FIGURE 15. RELATIONSHIP BETWEEN $\left[\frac{E}{P}\right]$ AND $[\tau]$ DATA (1915-1970) WITH 5-YEAR INTERVAL, EQUATION (IV.9).

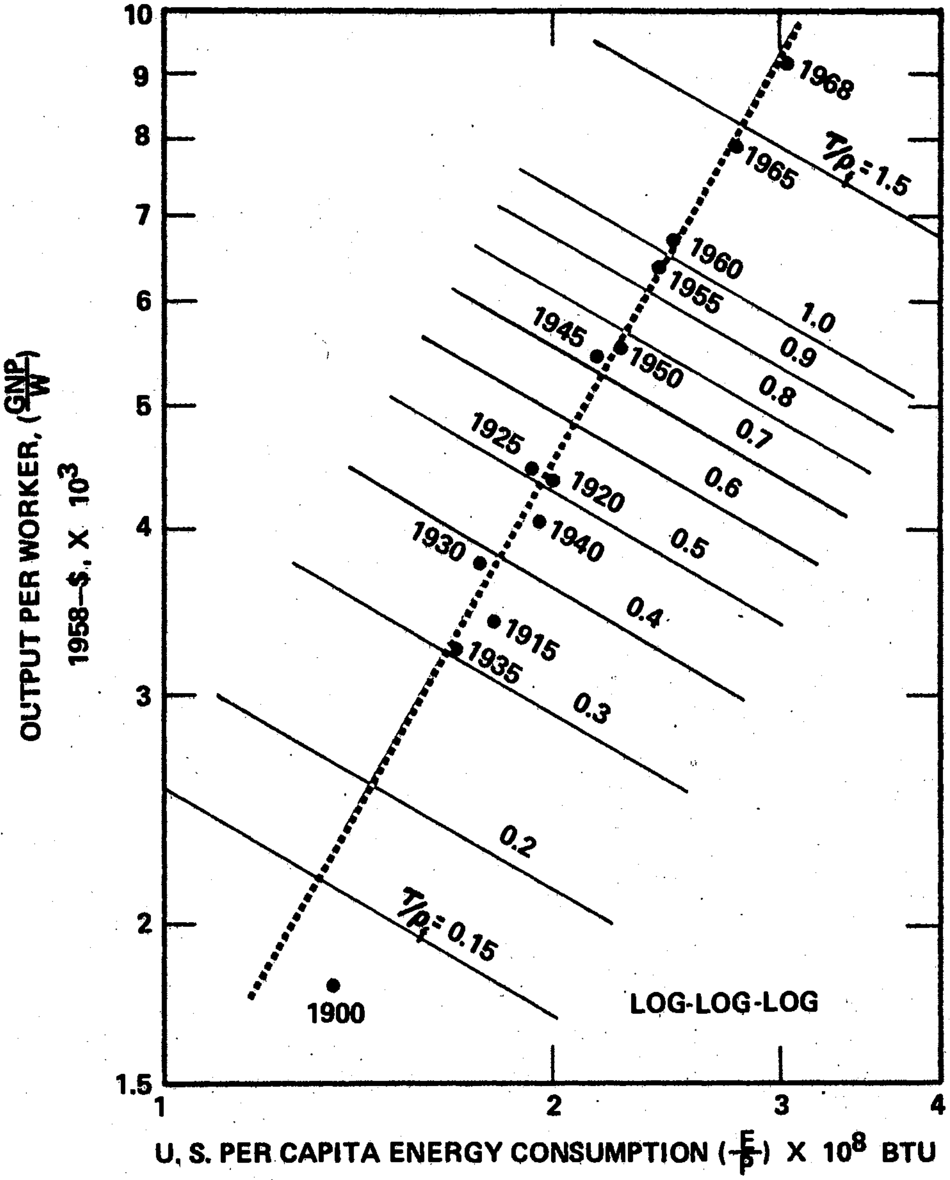

FIGURE 16. RELATIONSHIP BETWEEN $\left[\frac{E}{P}\right]$, $\left[\frac{GNP}{W}\right]_{1958}$ AND $\left[\frac{T}{\rho_f}\right]$ DATA (1915-1968) WITH 5 YEAR INTERVAL; EQUATION (IV.9)

where, k is a proportionality constant. By denoting the last term with appropriate symbols:

$$E = k \cdot [GNP]_{1958\ \$} \cdot \left[\frac{P}{W}\right] \cdot \left[\frac{\tau}{\rho_{a \cdot c}}\right]_{1958} \qquad (IV.10)$$

Model Version 2

$$E = k \cdot [GNP]_{current\ \$} \cdot \left[\frac{P}{W}\right] \cdot \left[\frac{\tau}{\rho_{a \cdot c}}\right]_{1958} \qquad (IV.11)$$

Model Version 3

$$E = k \cdot [Y_N]_{current\ \$} \cdot \left[\frac{P}{W}\right] \cdot \left[\frac{(\tau)}{\begin{pmatrix}\text{Average Whole Sale Price} \\ \text{of Fuel, per million BTU}\end{pmatrix}}\right]_{1958}$$

$$= k \cdot [Y_N]_{current\ \$} \cdot \left[\frac{P}{W}\right] \cdot \left[\frac{\tau}{\rho_f}\right]_{1958} \qquad (IV.12)$$

where $[Y_N]$ represents the U.S. national income.

Model Version 4

$$E = k \cdot [GNP]_{current\ \$} \cdot \left[\frac{P}{W}\right] \cdot \left[\frac{\tau}{\rho_f}\right]_{1958} \qquad (IV.13)$$

Model Version 5

$$E = k \cdot [Y_P]_{1958} \cdot \left[\frac{P}{W}\right] \cdot \left[\frac{\tau}{\rho_f}\right]_{1958} \qquad (IV.14)$$

where $[Y_P]$ represents the total personal income.

Model Version 6

$$E = k \cdot [GNP]_{1958} \cdot \left[\frac{P}{W}\right] \cdot \left[\frac{(\tau)}{\begin{pmatrix}\text{Average relative fuel}\\ \text{price per million BTU}\end{pmatrix}}\right]_{1958}$$

$$= k \cdot [GNP]_{1958} \cdot \left[\frac{P}{W}\right] \cdot \left[\frac{\tau}{\rho_r}\right]_{1958} \qquad \text{(IV.15)}$$

Figures 17 to 22 show the above six versions of the model represented by equations (IV.10 to (IV.15), respectively. The data for those figures are for the period 1915-1969.

Sources of Data

The data for the six parameters used in the proposed model (equation IV.9) are taken from various publications. The historical, time-series data on total energy consumption (E) was taken from the Minerals Yearbook, Vol. II (Fuels), published by the U.S. Bureau of Mines. The data on gross national product and national income (current and constant dollars) were taken from the 'Economic Report of the President' transmitted to the U.S. Congress and the annual reports of the Council of Economic advisors. Data pertaining to labor force, population, industrial production index and wholesale price index were taken from the 'Historical Statistics of the United States' and 'Long Term Economic Growth,' (U.S. Department of Commerce; Bureau of the Census).

Data concerning the future projections of the five exogenous (independent) parameters - (GNP), (P), (W), (τ) and (ρ) - were taken from several sources. The projections of GNP for the years 1980 and 2000 were obtained from the study, "Resources in America's Future" by

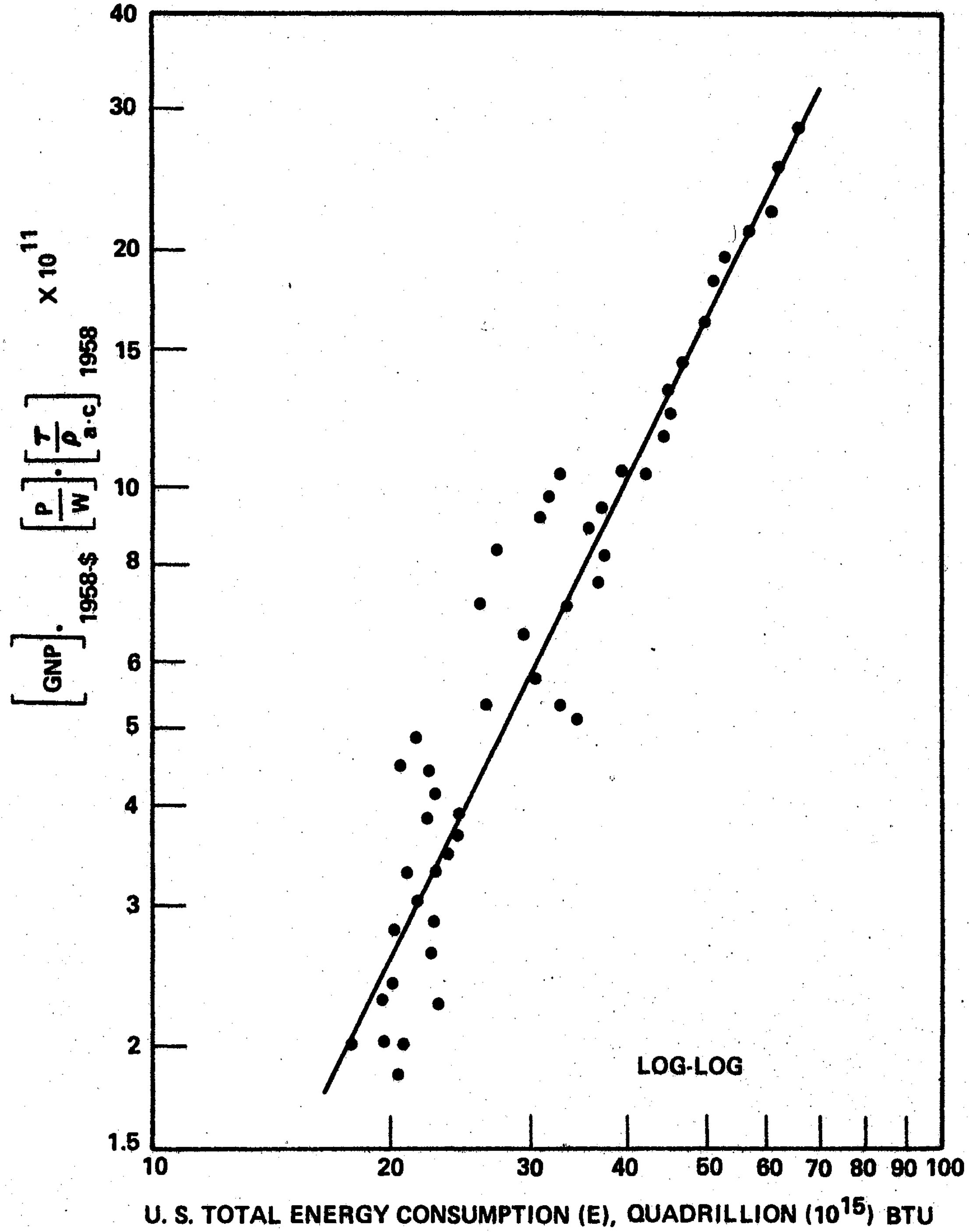

FIGURE 17. DATA (1915-1968) FOR THE TECHNO-ECONOMIC PARAMETERS, EQUATION (IV.10)

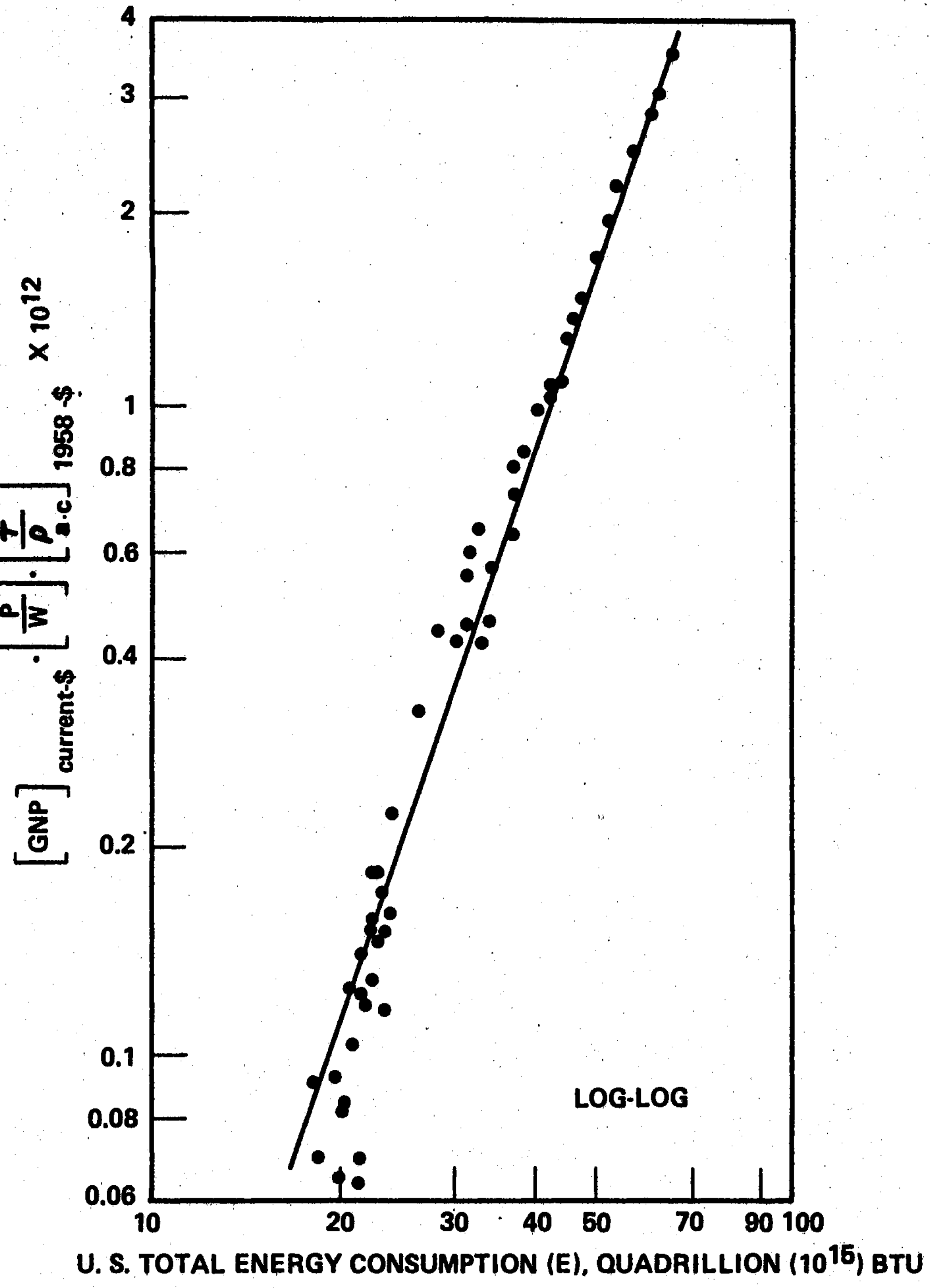

FIGURE 18. DATA (1915-1968) FOR THE TECHNO-ECONOMIC PARAMETER, EQUATION (IV. 11)

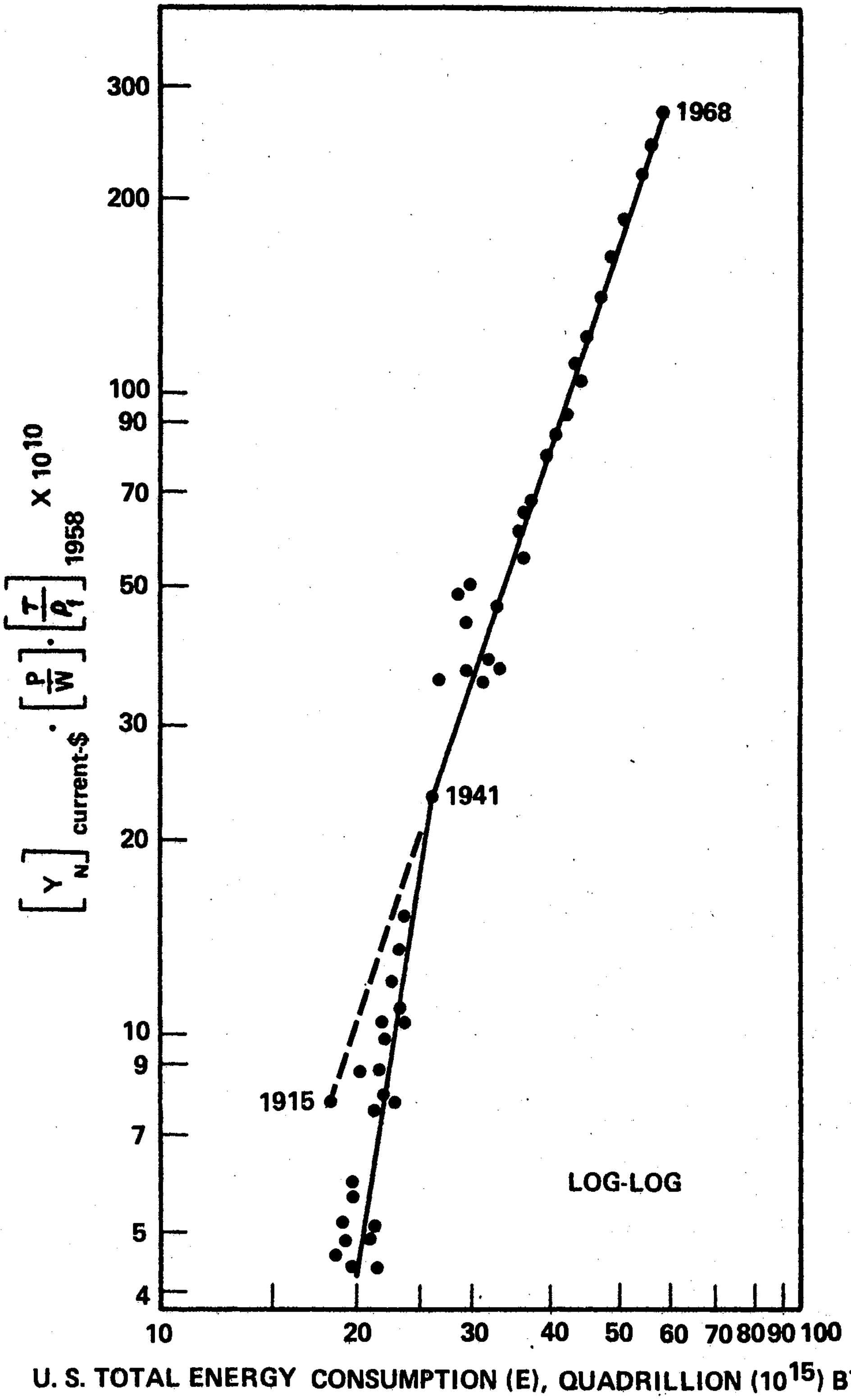

FIGURE 19. DATA (1915-1968) FOR THE TECHNO-ECONOMIC PARAMETERS, EQUATION (IV. 12)

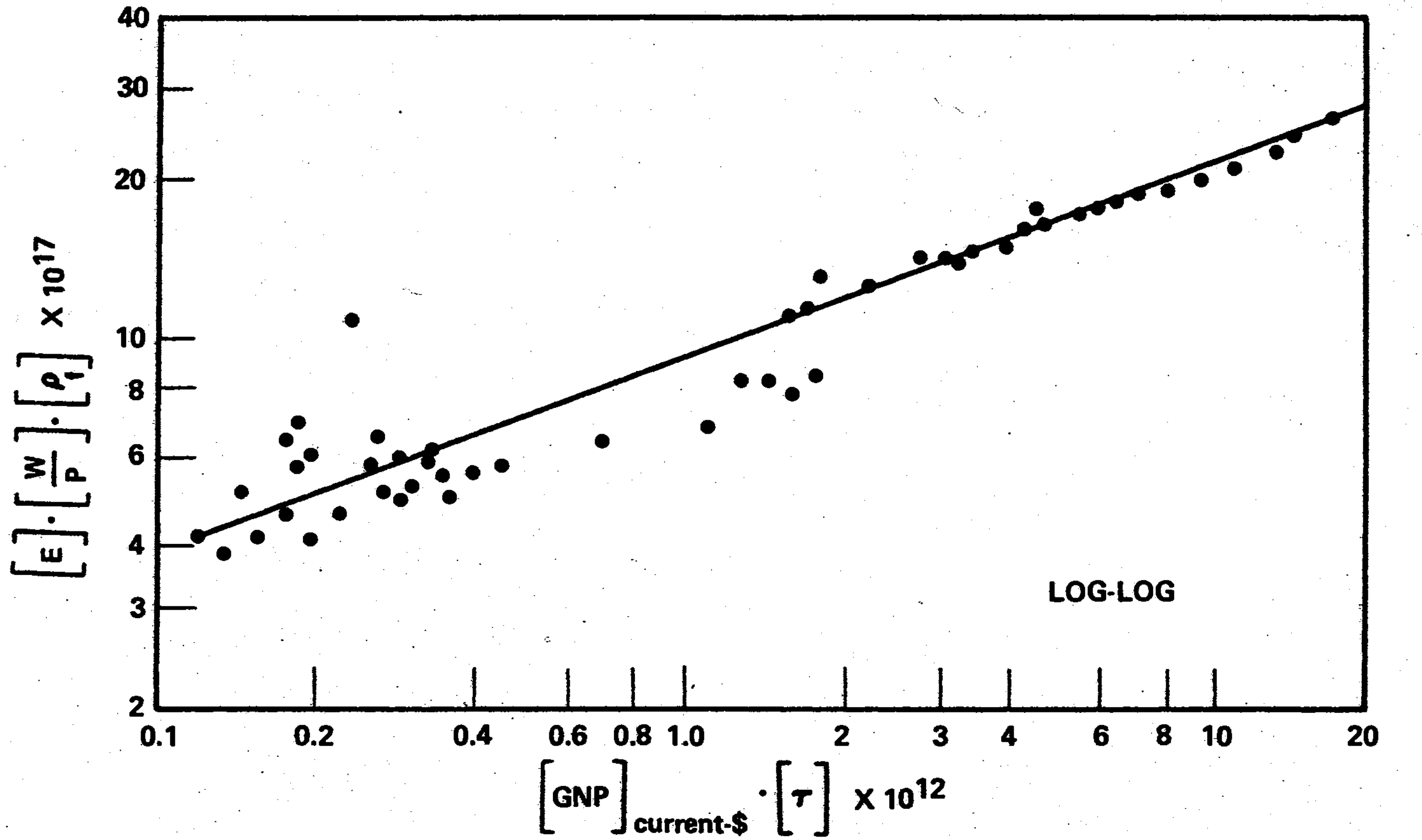

FIGURE 20. SHOWING DATA (1915-1968) FOR THE TECHNO-ECONOMIC PARAMETERS, EQUATION (IV. 13)

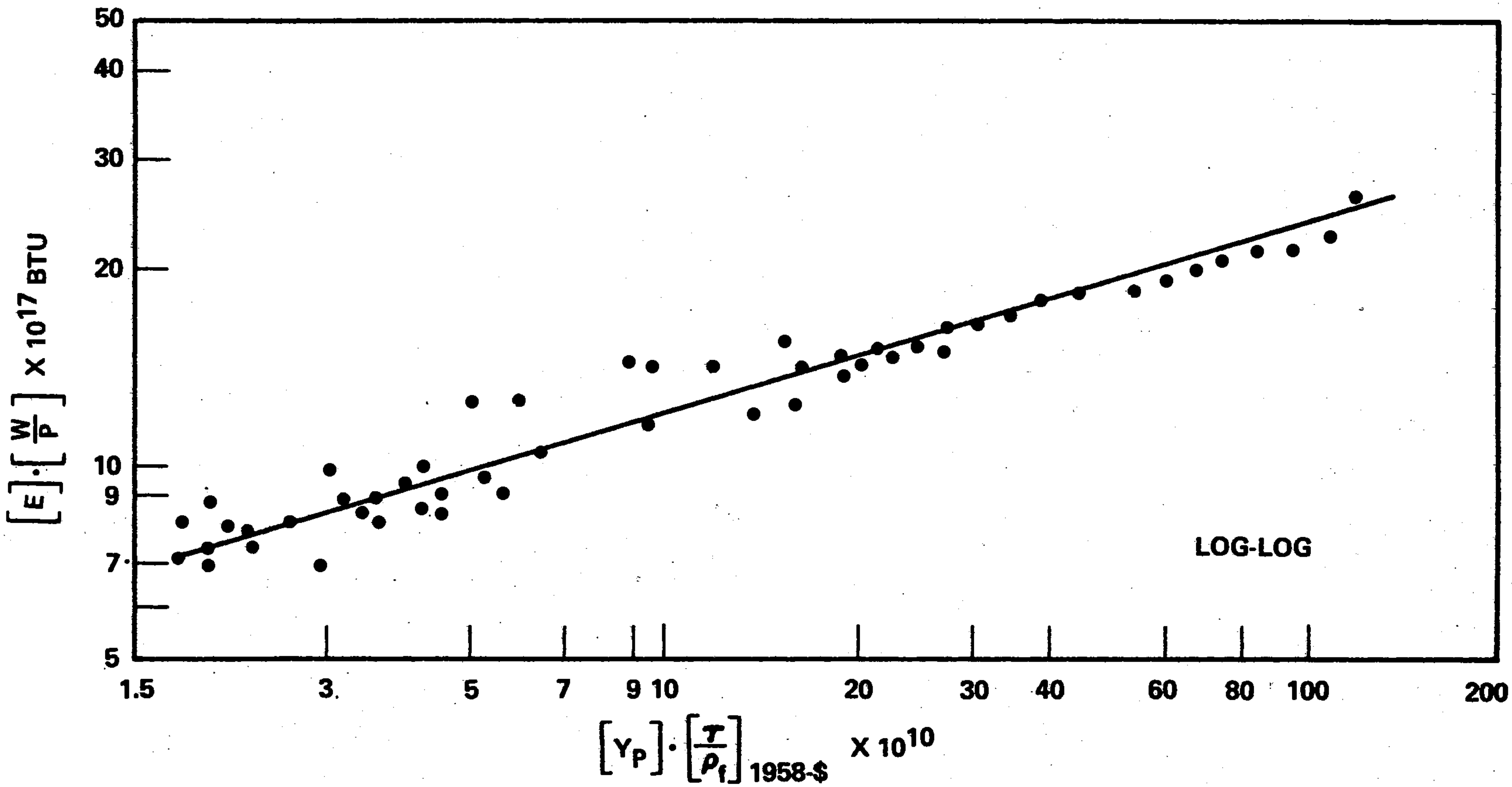

FIGURE 21. DATA (1915-1968) FOR THE TECHNO-ECONOMIC PARAMETERS, EQUATION (IV. 14)

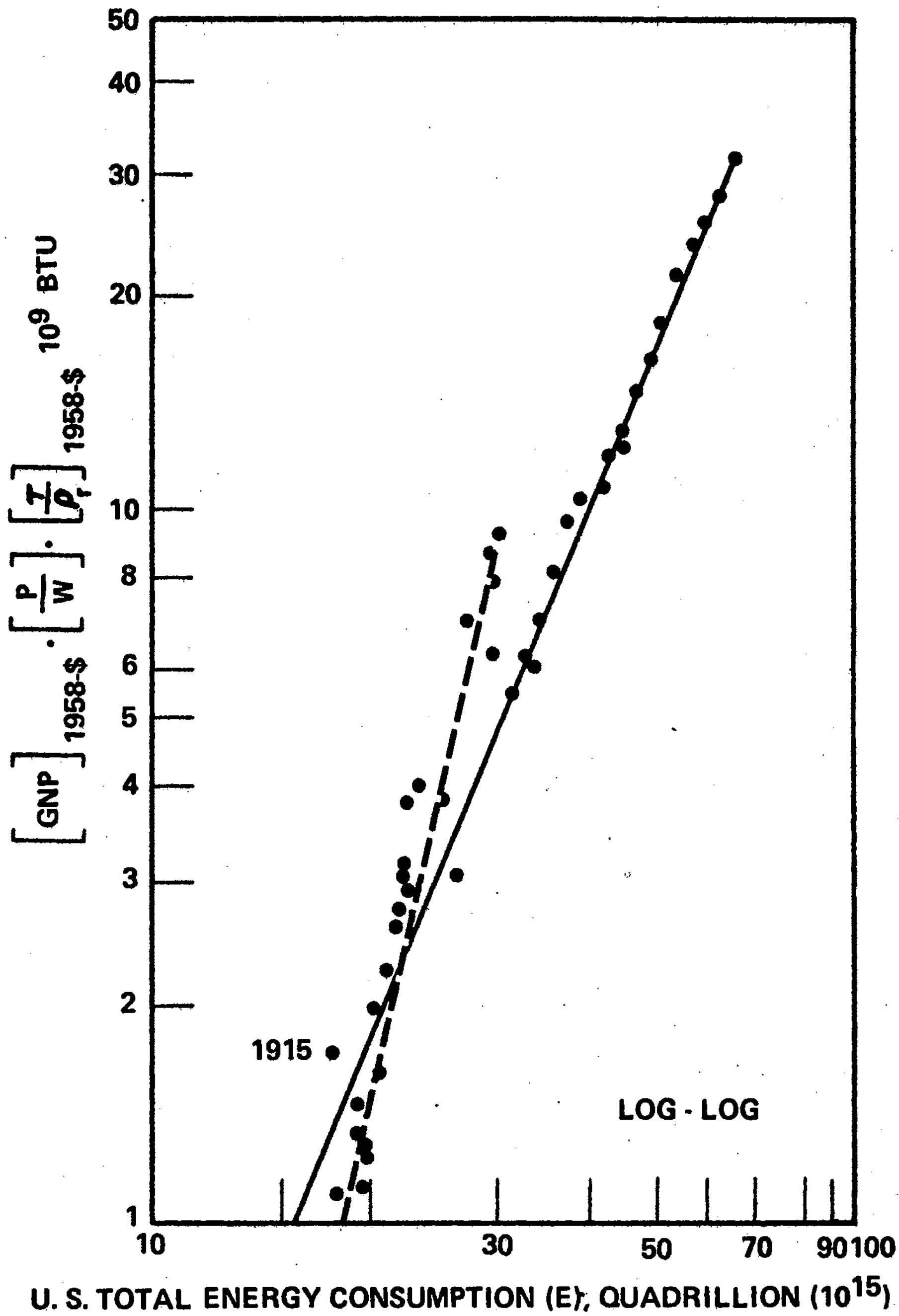

FIGURE 22. DATA (1915-1968) FOR THE TECHNO-ECONOMIC PARAMETERS, EQUATION (IV. 15)

Landsberg, Fischman and Fisher, (published by the Resources for the Future, Inc.). The study by Cooper and Johnston of the Bureau of Labor Statistics was heavily relied upon for data on (W) and (P). Projections concerning (τ) were based on the publications of the Federal Reserve Board; the future trends of (ρ) were taken from the estimates by the Department of Commerce for the wholesale price index. The calculations for the data on average fuel price per million BTU were based on various publications such as by Adelman (97), Sporn (61), American Gas Association (98) and Platt's Oilgram (99).

Derivation of a Prediction Equation

To make the task of forecasting U.S. total energy requirements relatively more convenient, a prediction equation is derived from equation (IV.9) describing the proposed techno-economic model.

$$f_5 \left[\left(\frac{E}{P}\right), \left(\frac{GNP}{W}\right), \left(\frac{\tau}{\rho}\right)\right] = 0 \qquad \text{(IV.9)}$$

In order to derive a prediction equation, it was decided to permute one grouping with a combination of the other two[13]. A system factor f_s is defined as the product of $\left[\left(\frac{GNP}{W}\right) \cdot \left(\frac{\tau}{\rho}\right)\right]$, and a plot is made between the system factor f_s and the grouping $\left(\frac{E}{P}\right)$. By fitting a least square line through the data for the period 1915-1970, the following equation is obtained:

[13]Although several possible permutations were tried, the one described above gave the best fit of data, and its index of multicollinearity was least of all the other groupings.

$$\left(\frac{E}{P}\right) = 1.369\ (f_s)^{0.3283} \times 10^4 \qquad \text{(IV.16)}$$

Substituting for the factor (f_s), the above equation becomes:

$$\left[\frac{E}{P}\right] = 1.369\ \left[\left(\frac{GNP}{W}\right) \cdot \left(\frac{\tau}{\rho}\right)\right]^{0.3283} \times 10^4 \qquad \text{(IV.17)}$$

The above equation is found to be dimensionally consistent; the units on both sides reduce to BTU; it is plotted in Figure 23.

Comparison of Proposed Methodology
With Others Published

a) The proposed methodology considers the U.S. energy economy system in terms of six select, aggregate parameters from an engineering (system) analysis point of view. This enables study of the composite effect of the five parameters - gross national product, population, labor force, level and spread of technology and price of energy - on U.S. total energy requirements. In contrast, the methodologies of most of the published forecasts are based on correlations of U.S. total energy requirements with one (or at most two) of the five variables stated above. In this respect, they tend to be piece-meal and not integrated in their approach.

b) Most published forecasts are derived by either statistically correlating and fitting of regression equations to historical, time-series data or by relying heavily on the so-called building-block approach. The proposed methodology emphasizes, instead, the interrelationships among the six select parameters.

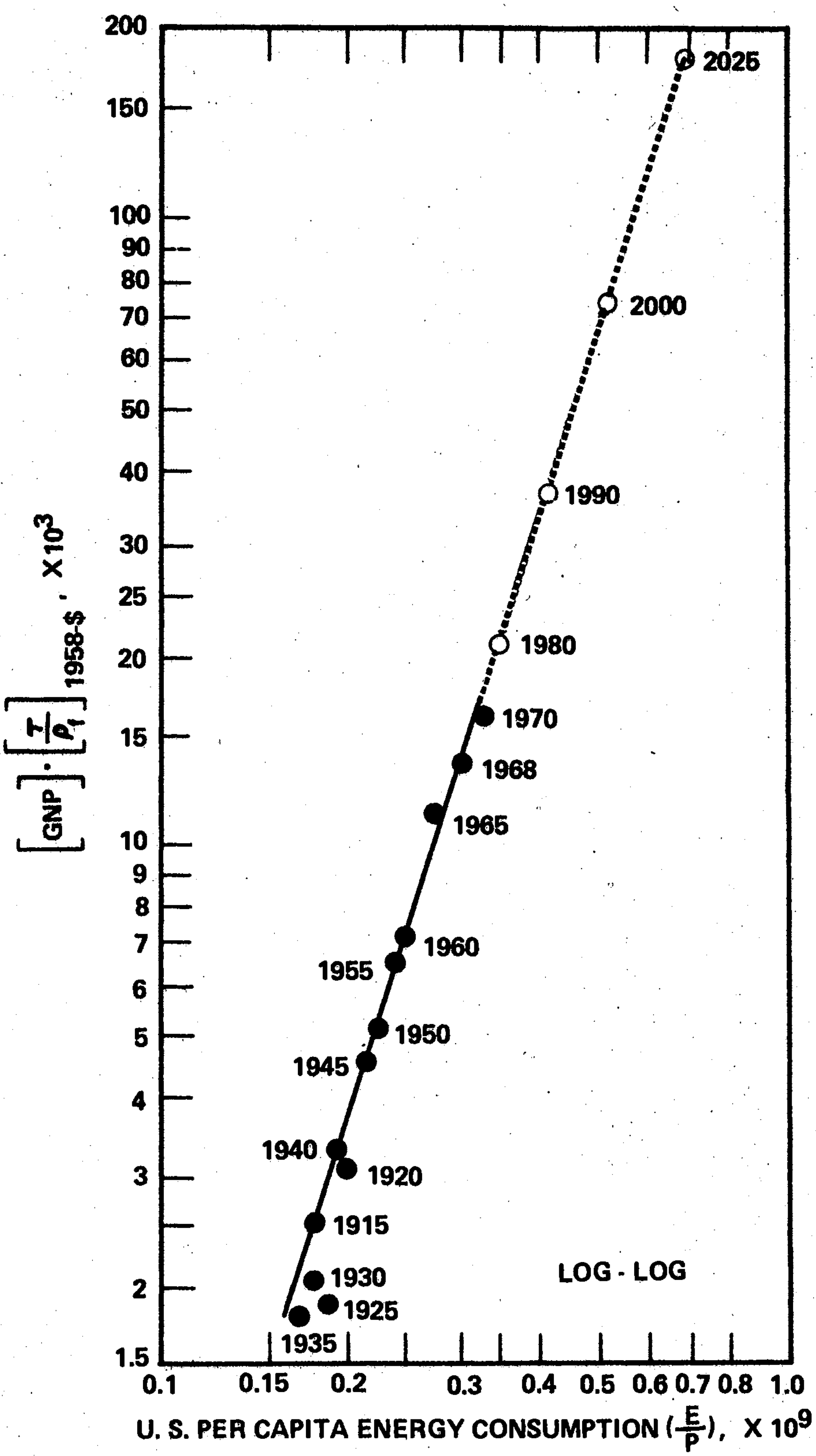

FIGURE 23. FORECASTS OF MODEL SIMULATIONS, (1970-2025), EQUATION (IV. 17)

c) The proposed methodology is based on an analysis of the historical, time-series data for the aggregate parameters (for the period 1915-1969). Although most other forecasts also utilize historical, time-series data, none is believed to be based on such a long span of time.

d) The proposed methodology incorporates, explicitly and numerically, the effects of changes in technology and price as relevant parameters over the forecast period (1970-2025). This is considered to be a unique characteristic of the proposed model.

CHAPTER V

RESULTS

On the basis of the methodology developed in the preceding chapter, four simulations of the proposed techno-economic model for the U.S. energy economy system are reported in Table III. These determine the U.S. total energy requirements for the years 1980, 1990, 2000 and 2025, and the forecasts for each of the five exogenous parameters used in model simulations. In computing the results, the basic set of assumptions stated in Chapter IV is utilized; however, several specific assumptions made for each of the four simulated models are given below:

Simulated Model for the Year 1980

The value of gross national product (GNP) is forecast assuming 5.0 percent per year growth rate for the period 1965-1980, (8). The rate of growth of population (P) is assumed to decrease by 1 percent of its value in the preceding year. The value for labor force employed (W) is taken as a compromise between the estimates of the labor participation rates by the Bureau of Labor Statistics (92), Texas Eastern (8), and the Resources for the Future (RFF), (10). It is also assumed that the U.S. industrial production index (τ) will continue to increase at an average of 3.7 percent per year during 1970-1980; this value closely approximates the estimates by Texas Eastern Study (8) and the RFF (10). Furthermore, the price of energy per million BTU (ρ) is assumed

TABLE III

FORECAST OF MODEL SIMULATION FOR
1980, 1990, 2000 AND 2025

	PARAMETER	SYMBOL	FORECAST VALUES FOR THE YEAR 1980	1990	2000	2025
1	U.S. Total Energy Requirements, quadrillion (10^{15}) BTU	(E)	91.1	122.8	169.2	300.3
2	U.S. Gross National Product, billion of 1958-$	(GNP)	1,280	1,996	3,115	7,455
3	U.S. Total Population, million	(P)	245	287	322	422
4	U.S. Labor Force employed, million of workers	(W)	100	119	134	173
5	Federal Reserve Board Index of Industrial Production	(τ)	246.8	341	564	1,456
6	Price of Energy per million BTU, 1958-$	(ρ)	132.8	155	185.8	348.3
7	Normalized Gross National Product, thousand of constant 1958-$	$\left(\frac{GNP}{W}\right)$	12.8	16.78	23.22	43.1
8	U.S. Per Capita Energy Requirements, million BTU	$\left(\frac{E}{P}\right)$	379.6	427.9	508.9	711.5

to increase at an average rate of 2.5 percent per year during the period 1970-1980. This assumption is based on the estimates of the 'Economist,' (100).

Simulated Model for the Year 1990

The gross national product is forecast to have 4.85 percent yearly growth rate for the period 1980-1990. The assumption with respect to population is the same as for the previous simulated model for the year 1980. The rates of increase for the industrial production index (τ) and price of energy (ρ) are taken as 3.7 and 2.0 percent per year, respectively, during the forecast period 1980-1990.

Simulated Model for the Year 2000

The gross national product is forecast to have 4.5 percent per year growth rate for the period 1990-2000. The assumptions with respect to the population parameter (P) and labor force employed ($\dot{W}$) are the same as in the simulated model for the year 1980. The rates of increase for the industrial production index (τ) and price of energy (ρ), during 1990-2000, are assumed to be 4.7 and 2.5 percent per year, respectively.

Simulated Model for the Year 2025

In view of the momentum that the U.S. economy would have gained by the year 2000, its gross national product is forecast to have 3.5 percent per year growth rate during the period 2000-2025. The estimates for population, labor force employed, industrial production index and price of energy are made by extrapolating their respective trends; (τ) and (ρ) are assumed to increase at 3.75 and 2.5 percent per year.

Energy - GNP Coefficients

Table IV shows the results of the coefficient of energy per unit of GNP produced and per capita energy consumption with respect to output per worker, in the U.S. economy, during the forecast period 1970-2025. These results are based on the rates of yearly change in total energy consumption, per capita energy consumption and output per worker, calculated for the ten-year intervals during the period 1915-2025.

Discussion of Results

The U.S. is endowed with huge resources of land, labor, capital and energy; however, no concerted effort has yet been made to formulate a long-term resources policy. In view of the U.S. economy being highly energy-intensive, serious questions of adequacy of energy resources, in particular, are being raised. All such questions, however, are centered around various aspects of energy forecasting in general and technological energy forecasting in particular.

Neither the concept nor the practice of energy forecasting is new; what is new, however, is the extent to which the need for reliable energy forecasts is being currently felt in the U.S. At least two exhaustive studies (8 , 10) have already been published and at least half a dozen less-exhaustive studies are reported in progress. However, with the exception of very few, all such studies are restricted to forecasts up to the years 1980 and/or 2000. Short-term energy forecasts - which may be simple extrapolations in which factors such as

TABLE IV

FORECAST RESULTS FOR THE U.S. ENERGY-ECONOMY SYSTEM

YEAR/YEAR INTERVAL	U.S. GROSS NATIONAL PRODUCT (GNP)		U.S. ENERGY REQUIREMENTS	
	Total (GNP), 1958 \$ × 10^9	Normalized GNP $(\frac{GNP}{W})$ 1958 \$ × 10^3	Total Energy (E), Quadrillion (10^{15}) BTU	Per Capita Energy Requirements $(\frac{E}{P})$, Million BTU
1915	137.4	3.45	18.1	180
1925	203.6	4.50	22.1	191.1
1935	169.5	3.22	21.4	168.1
1945	355.2	5.44	30.2	215.8
1955	438	6.36	40.1	242
1965	617.8	8.71	53.8	276.3
1980	1,280	12.80	91.1	379.6
1990	1,996	16.78	122.8	427.9
2000	3,115	23.22	169.2	508.9
2025	7,455	43.08	300.3	711.5
	GROWTH RATE, PERCENT PER YEAR			
1915 - 1925	3.95	2.65	2.0	0.55
1925 - 1935	-1.83	-3.30	-0.3	-1.37
1935 - 1945	7.71	5.35	3.45	2.51
1945 - 1955	2.15	1.75	2.80	1.05
1955 - 1965	3.52	3.18	2.96	1.31
1965 - 1980	4.95	2.55	3.50	2.11
1980 - 1990	4.85	2.70	3.0	1.15
1990 - 2000	4.5	3.25	3.2	1.71
2000 - 2025	3.5	2.45	2.25	1.30
	ENERGY-GNP COEFFICIENTS		$\left[\frac{E}{GNP}\right] \times 10^5$	$\left[\frac{E/P}{GNP/W}\right] \times 10^5$
1915	1.0	1.0	1.32	0.52
1925	1.0	1.0	1.09	0.42
1935	1.0	1.0	1.26	0.52
1945	1.0	1.0	0.85	0.38
1955	1.0	1.0	0.89	0.38
1965	1.0	1.0	0.89	0.32
1980	1.0	1.0	0.73	0.30
1990	1.0	1.0	0.62	0.25
2000	1.0	1.0	0.54	0.22
2025	1.0	1.0	0.40	0.17

population, changes in technology and prices are ignored - are generally made to assess market and supply conditions as in the case of coal and petroleum (22). More detailed medium-term forecasts are generally made to ascertain capital equipment investment to meet the expected demands. Finally, long-term energy forecasts provide a basis for examining possible alternative courses of economic development and help foresee energy problems. Such alternatives may result in policies affecting patterns of future energy supply and demand, transportation patterns, storage requirements, defense policies, etc., not to mention the modifications which may become feasible in tariffs and commerical policy. In addition, U.S. total energy forecasts of the type presented in this study may prove useful in the formulation of the following aspects of energy-policy:

a) to determine total energy requirements to achieve a target level of national output and to evaluate alternative plans of allocating national priorities for capital expenditures.

b) to formulate (public) energy policies commensurate with divergent constraints of environmental quality and increased energy demand.

c) to determine patterns of inter-fuel substitution, sources of supply and to ascertain optimum rates of exploitation of domestic energy resources.

The core of this study is the methodology on the basis of which the proposed techno-economic model for the U.S. energy economy system has been developed. The model is simulated to forecast the U.S. total energy requirements for the years 1980, 1990, 2000 and 2025. These forecasts are based on an integrated, engineering (system) analysis approach utilizing six aggregate techno-economic parameters - GNP, population, employed labor force, changes in level and spread of technology and price of energy. Within the limits of available data and the assumptions made, the forecasts have been made as diligently as possible; however, this author is under no illusion that time will not prove him wrong, or at least off the mark.

The results obtained by simulating the proposed techno-economic model for the years 1980, 1990, 2000 and 2025 are summarized in Tables III and IV. The results reported therein favorably compare with the average values of the other forecasts published and reported in Tables I and II. For instance, the average value of the sixteen forecasts reported in Table I for the year 1980 is 84.2×10^{15} BTU, as compared to the result of 91.1×10^{15} BTU of this study. Likewise, the average value of the eight forecasts reported in Table I for the year 2000 is 143.5×10^{15} BTU as compared to the result of 169.2×10^{15} BTU of this study. For the year 2025, the only available forecast gives a value of 252.2×10^{15} BTU by Felix (55). The forecast of this study is for 300.3×10^{15} BTU, about 19 percent higher. This difference is due to the fact that Felix had not considered changes in technology and price of energy which, on a long-term basis, become increasingly significant.

The results forecast for the period 1970-2025 show a continuous decrease in the trends of the energy - GNP coefficients, $\left(\frac{E}{GNP}\right)$ and $\left[\left(\frac{E}{P}\right) / \left(\frac{GNP}{W}\right)\right]$, except during the thirties and post-war years. These coefficients indicate gradual improvement in the utilization of energy per unit of output for the overall U.S. economy. In other words, the technical efficiency of the U.S. energy-economy system is forecast to gradually increase, as shown in Figure 24 and 25.

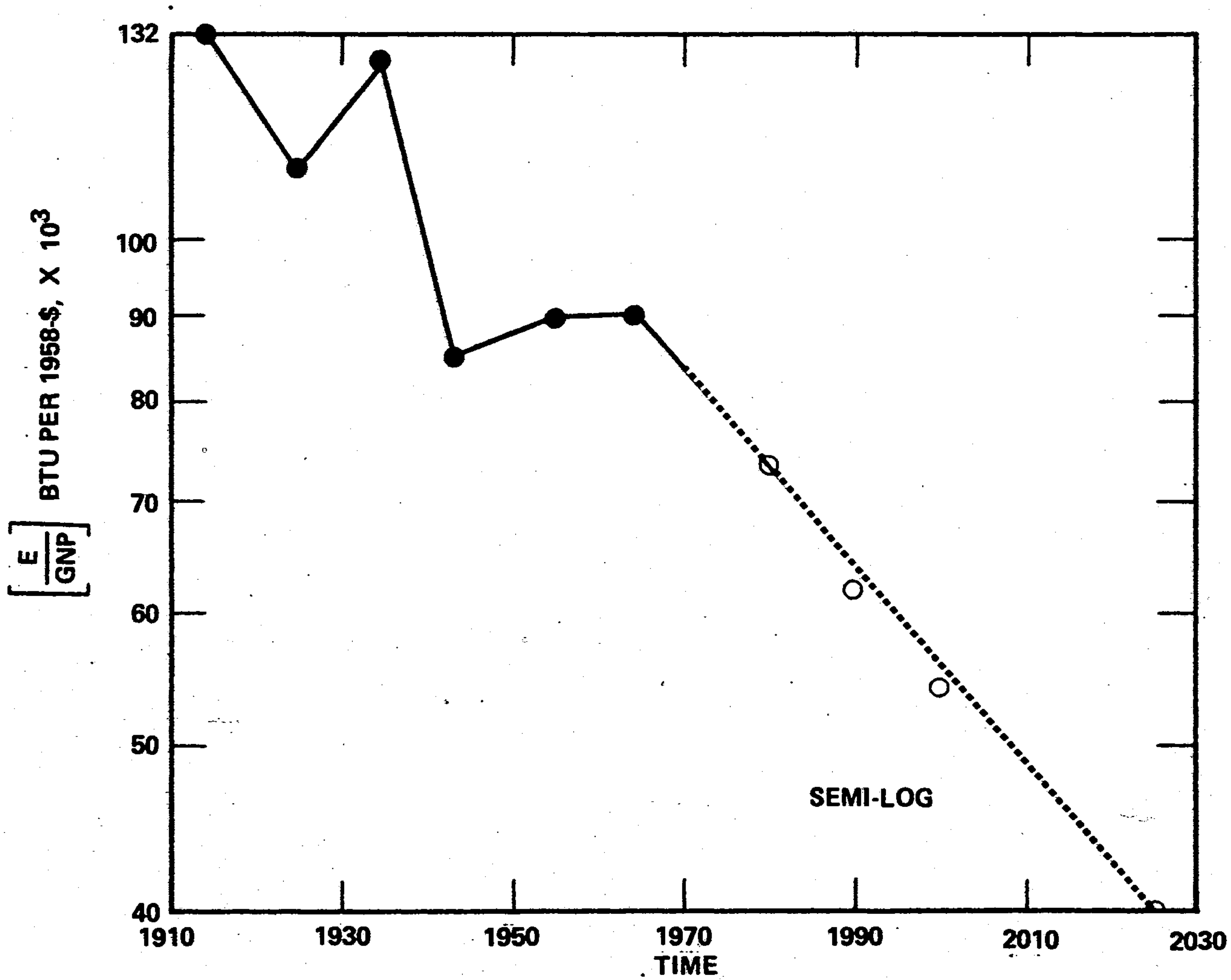

FIGURE 24. DECREASING TOTAL ENERGY REQUIREMENTS PER UNIT OF GNP, U. S. (1915-2025)

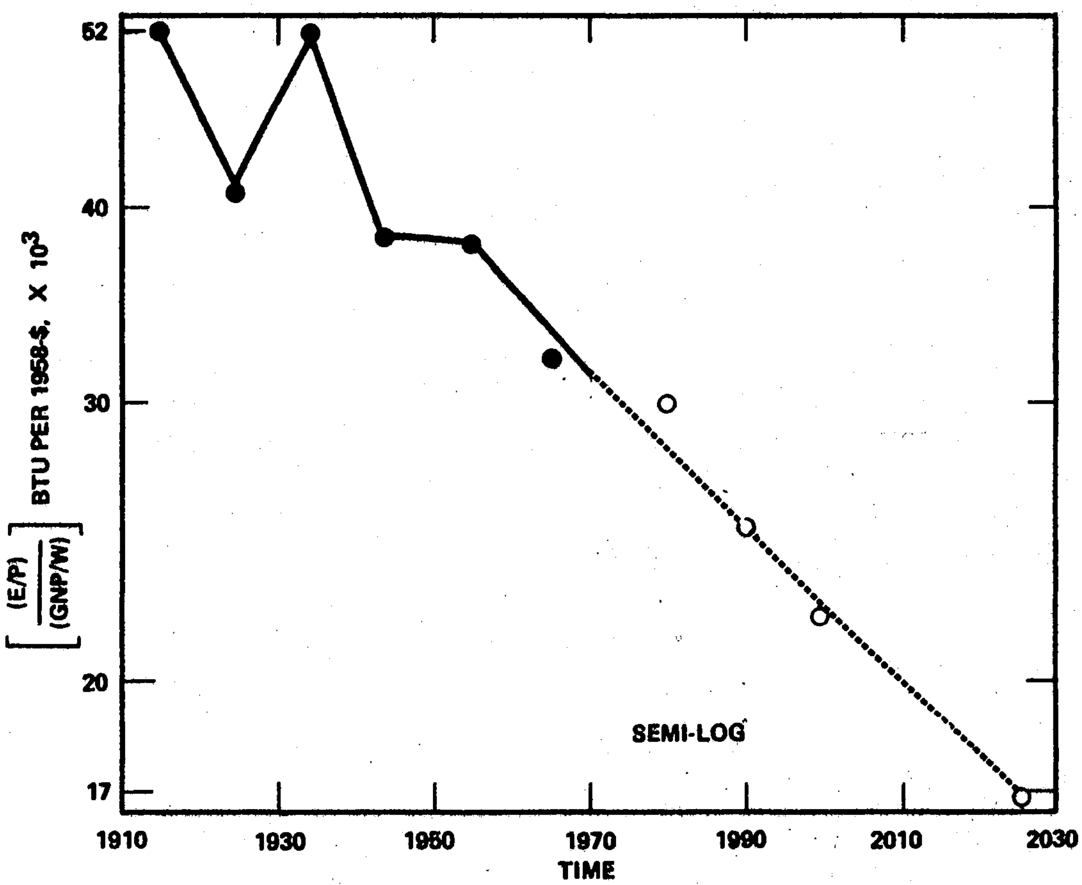

FIGURE 25. DECREASING U. S. PER CAPITA ENERGY REQUIREMENTS PER UNIT OF NORMALIZED GROSS NATIONAL PRODUCT, (1915-2025)

Although the results of this study compare favorably with three of the forecasts (9),(53),(60) reported in Table I, it should be noted that the assumptions of this study are not entirely comparable to those made by the above three authors. Each forecast is based on a set of assumptions which is neither explicitly stated nor does it correspond with the other two sets of forecasts. Morrison and Readling, for instance, have considered a range of growth rates, for the U.S. real GNP, from 2.5 to 5.5 percent per year. Their forecast GNP values, for the years 1980 and 2000, are 1,122 and 2,460 billion (1958-\$), respectively; these correspond to 4 percent per year growth rates during 1965-1980 and 1980-2000. But they did not incorporate the anticipated increase in the price of energy, in view of rising capital, construction and social (pollution) costs associated with utilization of energy.

Figure 23 shows a positive functional relationship between $\left[\frac{E}{P}\right]$ and the grouping $\left[\frac{GNP}{W} \cdot \frac{\tau}{\rho_f}\right]_{1958-\$}$ for the period 1915-2025, except the anomalies corresponding to the periods of the depression and 1920-1925. The anomaly with respect to the depression period is self-evident; however, the regression of the data point for 1925 may be viewed primarily in terms of the (relatively) lower technical conversion efficiency of plants and equipment at that time. Subsequently, several technological developments were witnessed: dieselization of trains, improved heat-rate of power generations, utilization of large prime movers in industry, etc. This is indicated by the elevated position of the data point for 1930 with respect to that of 1925. Similar changes in the patterns of energy conversion efficiency of plants and equipment may again be evidenced when the Breeder Reactor and/or non-polluting automobiles are introduced in the U.S. energy economy system.

In order to ascertain the stability of the proposed model, a sensitivity study was undertaken by varying the exogenous parameters within low, medium and high limits. For instance, three forecast values were computed by assuming the U.S. real GNP growth rate as 4, 4.5 and 5.0 percent per year, and the F.R.B. index of industrial production was assumed to vary from a low of 203 to a high of 305 for the year 1980. In all such cases, the U.S. total energy requirements forecast values ranged within ±11 percent.

In the final analysis, it should be appreciated that, from the very outset of this study, its primary objective has been to develop a methodology applicable to the U.S. energy economy system over the time span 1915-2025. The criterion of accuracy of results, though considered important for the study, is to be viewed in a relative setting only; the quality of results obtained are dependent upon the quality of the data used in the model itself. Since no effort was made to individually forecast the five exogenous techno-economic parameters (gross national product, population, labor force employed, level and spread of technology and price of energy), the quality of the forecast results is, therefore, limited by the quality of the data used in the model.

CHAPTER VI

EPILOGUE

Conclusions

a) The development of a numerical techno-economic model for forecasting the U.S. total energy requirements for 1980, 1990, 2000 and 2025 is feasible. The methodology is based on an engineering (system) analysis of historical time-series data for six techno-economic aggregate parameters namely, gross national product, population, labor force employed, level and spread of technology, price of energy and total energy requirements. The model affords generality in its application to either a developed country like the U.S. or a smaller region such as the State of Oklahoma or a developing country.

b) The proposed forecasting model is tested using the appropriate data for the six techno-economic parameters during the period 1915-1970. Using the prediction equation to simulate the model, the U.S. total energy requirements are forecast to be 91.1, 122.8, 169.2 and 300.3 quadrillion (10^{15}) BTU for the years 1980, 1990, 2000 and 2025, respectively.

c) The average vlues for the published forecasts (reported in Table I) for the years 1980, 2000 and 2025 are 84.2, 143.5 and 252.2 quadrillion (10^{15}) BTU, respectively. The increasing respective differences between these average values and the values forecast by this study show the significance of incorporating the parameters of level and spread of technology and price of energy.

d) The U.S. per capita energy consumption is forecast to be 379.6, 427.9, 508.9 and 711.5 million BTU for the years 1980, 1990, 2000 and 2025 respectively. By extrapolation, it is possible to forecast that per capita energy consumption may reach a billion (10^9) BTU by the year 2052. This forecast corresponds to 3.25 percent per year growth rate for real GNP (during 2025-2052), 40 percent labor participation rate and population of 525 million.

e) The results in Table IV show that the Energy-GNP coefficients (representing the contribution of energy to U.S. economy), will continue to decline gradually during 1970-2025. In other words, the technical efficiency of the U.S. economy is forecast to increase gradually.

Recommendations

a) Of the six techno-economic aggregate parameters used in the development of the proposed model, it was found most difficult to quantify the parameter of the level and spread of technology (τ). Although it is generally agreed that this parameter is a function of the availability of capital per worker in a given economy, it is recommended to study in detail several aspects of the relationship of this exogenous parameter with the others. Such a study at the interface of economics and engineering would be most helpful in further analyzing the behavior of the model.

b) This study is based on the assumption that the U.S. energy economy system is of a logarithmic linear form. Although this assumption is well documented by several published forecasts, it is recommended that a forecasting model should also be developed assuming the Gompertz S-curve form.

c) It is assumed that adequate energy resources at competitive prices will be available to meet the growing U.S. energy demand during the forecast period. This study has considered neither an evaluation of the forms of energy nor their sources to meet the forecast demand. There exists, therefore, a need for modifying the proposed techno-economic model in respect of the various energy resources - coal, oil, gas, etc. Such a study will lead to a closer examination of the technological and economic prospects for interfuel substitution to assist in the formulation of a long-term (national) energy policy.

d) In view of the specter of exhaustion of low-cost energy supplies on the one hand and the intimate relationship between energy consumption and environmental pollution on the other, there has been evidenced great enthusiasm to study energy-related issues in their respective institutional setting. It is also generally agreed that such issues can be best studied at the interface of various inter-related disciplines. Since energy plays such a key role in the progress of the developed and the developing countries alike, it is recommended that the Energy Resources Group efforts be broadened to an 'International Energy Institute' at Oklahoma State University with the collaboration of some international organization such as the United Nations or the World Bank.

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APPENDICES

APPENDIX A

GLOSSARY

BTU (British thermal unit) - The quantity of heat required to raise the temperature of one pound of water, at its maximum density, through one degree Fahrenheit.

Coal - Includes anthracite, bituminous, lignite, coke and coal chemicals.

Coal Chemicals - The materials recovered from the gases and vapors which result from the high-temperature carbonization of coal; essentially coke breeze, coke oven gas, tar, ammonium sulphate, ammonium liquor and light oils (8).

Consumption - This refers to an amount of energy resources (9) actually utilized in the past.

Degree-Day - A measure of the coldness of the weather experience, based on the extent to which the mean daily temperature falls below 65 degrees Fahrenheit.

Demand - This term may be used interchangeably with the term requirements; however, for the sake of consistency only the term 'requirements' has been used throughout this study.

Disposable Personal Income - The income that remains with persons after paying personal taxes and all other payments to the government.

Forecast - This refers to "an estimate of what future observations might be if the underlying process continues as it has in the past (93)."

The terms projection, prediction, anticipation, assessment, etc. may be used interchangeably but their use has been avoided due to terminological difficulties.

Fossil Fuels - Includes coal, petroleum, natural gas, excluding nuclear fuels. Fuels do not become energy sources until burned.

Goods - As a sector of gross national product, the dollar value of the materials produced (durable and non-durable) in the economy.

Gross National Product (GNP) - The total dollar value of all final goods and services produced by the economy at current market prices, before deduction of capital consumption charges. In this study only 'real' or 'constant dollar' GNP, with respect to 1958, is used. This is essentially a measure of physical output, and is obtained by dividing current dollar GNP by appropriate deflating indices.

Industrial Production Index (τ) - This index measures changes in the physical volume of output in manufacturing and mining. It reflects output changes at all stages within manufacturing, mining industries and public utilities, including intermediate as well as final products. The index does not include production on farms, in the construction industry, in transportation or in various trade and service industries. It is published by the Federal Reserve Board, periodically.

Kilowatt hour (Kwh) - A unit of energy equal to one thousand watts acting for one hour. It is equivalent to 3,412 BTU.

Labor Force Employed (W) - This includes the total labor force employed including the armed forces, as defined by the Department of Labor, Bureau of Labor Statistics in their series, "Employment and Earnings of Monthly Report on the Labor Force."

Model - A representation of a system under study.

Multiple Regression Analysis - This type of analysis attempts to relate a series of data to some independent variables with the purpose of arriving at the best mathematical equation which can be used to explain past activity or to forecast future activity.

Personal Income - The sum of wages and salary disbursements, other labor income, proprietor's income, rental income of persons, dividends, personal interest income and transfer payments, less personal contributions for social insurance.

Petroleum - This refers to the whole range of petroleum products consumed in various sectors of the economy. For instance, in case of petroleum usage in the transportation sector, it includes gasoline, LP Gas, aviation fuel, jet fuel, heavy fuel oil, diesel, etc.

Plant Factor - The ratio of the output of an electric generating plant to its rated capacity, over a given period of time.

Q BTU - This equals a thousand quadrillion BTU (10^{18}).

Quadrillion BTU - This equals 10^{15} BTU.

Requirements - This refers to an amount of energy resource (5) forecast to meet future needs, taking into view the anticipated changes in GNP, technology, price, and shifts in population and labor force.

Services - As a sector of gross national product, the dollar value of the output of those areas of the economy in which the final product is not a good; instead is the performance of a service such as medical services, rental value of housing, personal care, recreation facilities, private education, research, religious and welfare activities, etc.

System - An ordered arrangement of several physical or abstract elements, interrelated to one another and functioning together.

System Analysis - The study of the elements, relationships and procedures of a system to achieve a specific purpose.

Techno-Economic (model) - A (model) which lies at the interface of technology and economics and requires an interdisciplinary approach for its analysis.

Total Energy Consumption (E) - This includes the total amount of energy (in BTU) consumed by an economy for a certain given level of economic activity. It includes the physical losses at the point of utilization which may vary from 10 to 15 percent.

Trillion BTU - This equals 10^{12} BTU.

Wholesale Average Price of Fuel [ρ_f] - This includes an average of the prices of coal, oil and gas on a million BTU bases.

APPENDIX B

PARTIAL LIST OF APPLICATIONS OF TECHNOLOGICAL FORECASTING

	AREA OF APPLICATION	FORECASTER	YEAR
1.	Automobiles, aviation, energy, wars	H. G. Wells	1901
2.	Inventions, patents	S. C. Gilfillan	1935
3.	Lengths of ships (1840 to 1960)	S. C. Gilfillan	1912
4.	Project HINDSIGHT, U.S. Army	R. S. Isenson	1965
5.	Average automotive h.p. vs. time	R. C. Lenz, Jr.	1960
6.	Specific fuel consumption - Elec. Gen. plants (1900 - 2000)	R. C. Lenz, Jr.	1960
7.	Speed trends of U.S. Combat Aircraft (1930 - 2100)	R. C. Lenz, Jr.	1962
8.	Total Passenger in domestic airlines (1930 - 2000)	R. C. Lenz, Jr.	1960
9.	Automotive Trends (h.p. and vehicles per capita 1900 - 2000)	R. C. Lenz, Jr.	1961
10.	Cargo Aircraft development project	R. C. Lenz, Jr.	1965
11.	Accelerator energy 1930 - 1960	R. U. Ayres	1966
12.	Computer mushrooming 1940 - 1980	R. U. Ayres	1960
13.	Efficiency of external combustion energy conversion systems (1700-2000)	R. U. Ayres	1965
14.	Dollar value of GNP and R & D (1945-2000)	A. L. Floyd	1960
15.	Number of Electric Road Vehicles (1953-83)	A. L. Floyd	1960
16.	Crude oil supply stocks in the U.S.(1953-83)	U.S. Dept. Int.	1963
17.	Study of speed trends of vehicles (1800-2350)	D. G. Samaras	
18.	50% electric automobiles on road	Olaf Helmer	1967
19.	Thermo-nuclear fusion becomes competitive with hydro-electric power	Olaf Helmer	1967
20.	First landing on moon and stay there a month by man	Olaf Helmer	1967
21.	When will medium family income double?	Olaf Helmer	1967
22.	Air cushion vehicles (1960-1990)	M. J. Cetron	1965
23.	Solid state amplifiers	M. J. Cetron	1960
24.	Melting point of metals (1960-1970)	M. J. Cetron	1961
25.	ICBM Trajectory	U.S. Army	1960
26.	Nuclear Weapons	U.S. Army	
27.	Project PATTERN, IMPACT, etc.	Rand Corp.	1960
28.	Increase in Knowledge, Project MIRAGE	U.S. Army	1965
29.	The world of 2000: Political horizons	H. A. Linstone	1967
30.	Coal demand 1945-1980		
31.	Planning-programming-budgeting system (PPBS)	R. S. McNamara	1960's

APPENDIX C

EFFECTS OF TECHNOLOGICAL CHANGE, LABOR, CAPITAL AND ENERGY INPUTS ON U.S. OUTPUT

The subject area of technological change, labor and capital inputs in relation to the U.S. output has been extensively studied by several economists (101,102,103). In addition, Solow (104) has shown the relationship between technological change and an aggregate production function, thus:

$$Q = F(K,L;t) \tag{C.1}$$

where, Q represent output and K and L represent capital and labor inputs in physical units, respectively. The variable (t) denotes technological change which is defined as "any kind of shift in the production function." Therefore, economic slowdown, business downturns, speed-ups, improvements in the education and skill of labor, etc. - all these are regarded as technological change. Solow has further defined the "shifts in the aggregate production function as neutral if they leave marginal rates of substitution untouched but simply increase or decrease the output attainable from given inputs. In that case, the above equation takes the form:

$$Q = A(t)f(K,L) \tag{C.2}$$

and, the multiplicative factor $A(t)$ measures the cumulative technological change over a period of time. By applying the above approach to the U.S. economy during 1909-1949, he has shown that the output-per-worker $\left(\frac{Q}{L}\right)$ evaluated per unit of $A(t)$, is a positively sloped straight line when plotted against the variable of capital-per-worker $\left(\frac{K}{L}\right)$.

His main conclusions are the following. The over-all result for the 40 year period in the U.S. economy shows an average upward technological change of about 1.5 percent per year. Also, the labor productivity (output per man-hour) approximately doubled, with 87.5 percent of the increase attributable to technological change and the remaining 12.5 percent to increased use of capital. Lastly, the technological change during the study period (1909-1949) remained neutral on average.

Effect of Energy Input on National Output

Several authors have endeavored to analyze the general U.S. economic productivity (105,106,107); of these, Dewhurst's work (105) is perhaps the most extensive one. He has estimated that during 1850-1950, the national income of the U.S. increased (in 1950-$) from 9.3 to 239 billion dollars. This increase of 25 times was accompanied by a slightly more than 4 times increase in the total labor input (from 26 to 113 billion man-hours worked). As a result, the average net product per man-hour increased from 34 cents in 1850 to #1.92 in 1950. This spectacular increase is generally interpreted in terms of labor productivity or even as a measure of national productivity; however, it measures neither of the two since the U.S. economy does not consist of labor alone as an input. The inputs of fixed and circulating capital have to be considered as well.

Dewhurst has also calculated that the total input of primary energy to the U.S. economy increased from 710 to 9201 million megacalories, about 13 times increase during 1850-1950. In a broader context of energy, therefore, a concept of over-all economic productivity (η_e) may be defined as the ratio of national income to primary energy consumption. Applying this concept to the U.S. economy during 1850-1950:

$$\frac{\text{National Income(1950)}}{\text{National Income(1850)}} = \frac{\text{Primary Energy required(1950)}}{\text{Primary Energy required(1850)}} \cdot \frac{\text{Economic Productivity(1950)}}{\text{Economic Productivity(1850)}} \tag{C.3}$$

or,

$$25 = (13) \cdot \frac{(\eta_e \text{ in } 1950)}{(\eta_e \text{ in } 1850)} \tag{C.4}$$

$$\eta_{e(1850-1950)} = 1.92 \tag{C.5}$$

The over-all economic productivity of the U.S. economy increased 92 percent during 1850-1950. This measure of productivity should not be confused with the efficiency of energy transformation into useful work which, during the said period, increased from 8.2 percent to 13.8 percent, i.e. about 70 percent.

From the foregoing remarks, it is concluded that the great increase in both the U.S. national income and average net product per man-hour was due to an enormous influx of energy from inorganic sources and, to a lesser extent, due to the improvement in the efficiency of energy transformation.

APPENDIX D

COMPUTER ANALYSIS OF THE TECHNO-ECONOMIC PARAMETERS USED IN THE MODEL

On the basis of an extensive literature survey, a set of seventeen techno-economic parameters reported to correlate with some measure of energy consumption, was chosen for further study. It was decided to use the versatility of the IBM 360 computer and the cal-comp plotter #565, to study the interrelationships of these parameters. In the first phase of work, thirty eight computer plots of various parameters amongst themselves w.r.t. time were made. These plots were primarily intended to study the variations of the techno-economic parameters such as, total energy consumption, gross national product (in current and constant dollars), labor participation rate, Federal Reserve Board's index of industrial production, wholesale price index for all commodities (1958-$), wholesale price index for fuel and related products (1958-$), consumer price index for all items, national income and personal income, both in current dollars. Several permutations of these nine parameters were also tried. In each case polynomials of degree one through five were fitted and the percentage minimum squared error and the polynomial coefficients were evaluated. From a study of these time-series plots, a set of six techno-economic parameters was selected for the development of the proposed model representing the U.S. energy economy. These six parameters are: total energy consumption, gross national product (1958-

$), population, labor force employed, industrial production index and price of energy.

With appropriate modifications in the aforementioned computer program, the above six techno-economic parameters were plotted to ascertain the validity of the basic model equation (IV.9), described in Chapter IV, Figures 17 to 22. The main computer program and the sub-routines used in the study of interrelationships among the techno-economic parameters is given in the following pages.

```
      DIMENSION C(50)
      DIMENSION ROWAC(100),ROWF(100)
      DIMENSION IX(10),DT(100),GNPC(100),PCON(100),GNP58(100),
     $PCON58(100),YN(100),YP(100),TOU(100),COL10(100),COL11(100),
     $COL12(100),RL(100),X(100),Y(100)
    1 FORMAT(3I5)
    2 FORMAT(20I1)
    3 FORMAT(F10.0)
  777 FORMAT(1X,10E17.7)
  888 FORMAT(1X,'DEGREE OF THE POLYNOMIAL=',I3,'MINIMUM SQUARED ERROR='
     $,E14.7)
      READ(5,1)NYEARS,NGRAPH,NDATA
      READ(5,2)(IX(I),I=1,NGRAPH)
      DO 1000 I=1,NDATA
      DO 2000 J=1,NYEARS
      GO TO(51,52,53,54,55,56,57,58,59,60,61,62,63,64,65),I
   51 CONTINUE
      READ(5,3)DT(J)
      GO TO 2000
   52 CONTINUE
      READ(5,3)GNPC(J)
      GO TO 2000
   53 CONTINUE
      READ(5,3)PCON(J)
      GO TO 2000
   54 CONTINUE
      READ(5,3)GNP58(J)
      GO TO 2000
   55 CONTINUE
      READ(5,3)PCON58(J)
      GO TO 2000
   56 CONTINUE
      READ(5,3)YN(J)
      GO TO 2000
   57 CONTINUE
      READ(5,3)YP(J)
      GO TO 2000
   58 CONTINUE
      READ(5,3)TOU(J)
      GO TO 2000
   59 CONTINUE
      READ(5,3)COL10(J)
      GO TO 2000
   60 CONTINUE
      READ(5,3)COL11(J)
      IR=J
      ROWAC(IR)=TOU(IR)/COL11(IR)
      GO TO 2000
   61 CONTINUE
      READ(5,3)COL12(J)
      IR=J
      ROWF(IR)=TOU(IR)/COL12(IR)
      GO TO 2000
   62 CONTINUE
      READ(5,3)RL(J)
      GO TO 2000
   63 CONTINUE
   64 CONTINUE
```

```
      65   CONTINUE
      2000 CONTINUE
      1000 CONTINUE
           DO  300  K=1,NGRAPH
           DO  200  M=1,NYEARS
           GO TO(11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30)
          $,K
      11   CONTINUE
           X(M)=DT(M)
           Y(M)=GNPC(M)
           GO TO 200
      12   CONTINUE
           X(M)=DT(M)
           Y(M)=GNP58(M)
           GO TO 200
      13   CONTINUE
           X(M)=DT(M)
           Y(M)=RL(M)
           GO TO 200
      14   CONTINUE
           X(M)=DT(M)
           Y(M)=1.00/RL(M)
           GO TO 200
      15   CONTINUE
           X(M)=DT(M)
           Y(M)=ROWAC(M)
           GO TO 200
      16   CONTINUE
           X(M)=DT(M)
           Y(M)=ROWF(M)
           GO TO 200
      17   CONTINUE
           X(M)=GNPC(M)
           Y(M)=RL(M)
           GO TO 200
      18   CONTINUE
           X(M)=GNP58(M)
           Y(M)=RL(M)
           GO TO 200
      19   CONTINUE
           X(M)=GNPC(M)
           Y(M)=1.00/RL(M)
           GO TO 200
      20   CONTINUE
           X(M)=GNP58(M)
           Y(M)=1.00/RL(M)
           GO TO 200
      21   CONTINUE
           X(M)=GNPC(M)
           Y(M)=ROWAC(M)
           GO TO 200
      22   CONTINUE
           X(M)=GNP58(M)
           Y(M)=ROWAC(M)
           GO TO 200
      23   CONTINUE
           X(M)=GNPC(M)
           Y(M)=ROWF(M)
```

```
            GO TO 200
      24    CONTINUE
            X(M)=GNP58(M)
            Y(M)=ROWF(M)
            GO TO 200
      25    CONTINUE
            X(M)=RL(M)
            Y(M)=ROWAC(M)
            GO TO 200
      26    CONTINUE
            X(M)=RL(M)
            Y(M)=ROWF(M)
            GO TO 200
      27    CONTINUE
            X(M)=1.00/RL(M)
            Y(M)=ROWAC(M)
            GO TO 200
      28    CONTINUE
            X(M)=1.00/RL(M)
            Y(M)=ROWF(M)
            GO TO 200
      29    CONTINUE
      30    CONTINUE
      200   CONTINUE
            CALL XYPLOT(X,Y,NYEARS,9.0,9.0)
            DO  77  II=1,5
            CALL  CURVFT(X,Y,NYEARS,II,C,E)
            NUMC=II+1
      99    FORMAT(1X,'**********************************************')
            WRITE(6,99)
            WRITE(6,888)II,E
            WRITE(6,777)(C(I),I=1,NUMC)
            WRITE(6,99)
      77    CONTINUE
      300   CONTINUE
            STOP
            END
```

```
FORTRAN IV G LEVEL  18            XYPLOT            DATE = 71068        20/00/33           PAGE 0001

 0001              SUBROUTINE XYPLOT(X,Y,NP,XLINCH,YLINCH)
             C-----
             C          SUBPROGRAMME REQUIREMENT
             C          SUBROUTINE ORDER(PGINTS,N,NORDER)
             C-----
 0002              DIMENSICN X(1),Y(1),NCF(225)
 0003              REAL*8 IPLOT(12),IMINUS(12),IPOINT(8),IAXIS(8),IZAXIS(12),IB
 0004              REAL*8 IFIRST(8),ILAST(8)
             C-----
 0005              DATA IPOINT, IAXIS/8H*        ,8H *      ,8H  *     ,8H   *    ,8H
                  1    *   ,8H     *  ,8H      * ,8H       *,8H|      ,8H |     ,8H
                  2 |      ,8H   |    ,8H    |   ,8H     |  ,8H      | ,8H       |/
 0006              CATA IB,IMINUS/8H        ,12*8H________/
 0007              DATA IZAXIS,IPLCT/24*8H        /
 0008              CATA IFIRST,ILAST/8H*       ,8H|*      ,8H| *     ,8H|  *    ,8H|
                  1   *    ,8H|    *   ,8H|     *  ,8H|      *,8H*      |,8H *     |,8H
                  2*     |,8H   *   |,8H    *  |,8H     * |,8H      *|,8H       */
             C-----
 0009            1 FCRMAT(1H1,5X,'X',9X,'Y(X)',4X,12A8)
 0010            2 FORMAT(1X,E10.3,1X,E10.3,2X,12A8)
 0011            3 FCFMAT(1H+,23X,12A8)
 0012            4 FORMAT(24X,12A8)
             C-----
 0013              XSIZE = XLINCH*6.0
 0014              PLSIZE = YLINCH*10.0
 0015              IF(PLSIZE.GT.96.0) PLSIZE = 96.0
 0016              IF(PLSIZE.LT.8.0) PLSIZE = 8.0
 0017              NSIZE = PLSIZE/8.0
 0018              NYSIZE = NSIZE*8
 0019              PLSIZE = NYSIZE - 1
             C-----
 0020              CALL ORDER(X,NP,NOR)
 0021              XMIN = X(NOR(1))
 0022              XMAX = X(NOR(NP))
 0023              DX = XMAX - XMIN
             C-----
 0024              YMIN = Y(1)
 0025              YMAX = Y(1)
 0026              DO 20 I=1,NP
 0027              IF(Y(I).LT.YMIN) YMIN = Y(I)
 0028           20 IF(Y(I).GT.YMAX) YMAX = Y(I)
 0029              IF(YMIN.NE.YMAX) GO TO 21
 0030              IF(YMIN.LT.0.0) YMAX = 0.0
 0031              IF(YMIN.EQ.0.0) YMAX = 1.0
 0032              IF(YMIN.GT.0.0) YMIN = 0.0
 0033           21 DY = YMAX - YMIN
 0034              YMNMX = YMIN*YMAX
             C-----
 0035              IF(YMNMX.LT.0.0) GO TO 10
 0036              NYZ = 1
 0037              IZDIF = 1
 0038              GO TO 12
             C-----
 0039           10 IZERO = - YMIN/DY*PLSIZE + 1.5
 0040              IZ88 = IZERO/8
 0041              IZDIF = IZERO - IZ88*8
 0042              NYZ = IZ88 + 1
 0043              IF(IZDIF.NE.0) GO TO 12
```

```
      NYZ = IZB8
      IZDIF = 8
C-----
   12 IZAXIS(NYZ) = IAXIS(IZDIF)
      IZAXIS(1) = IAXIS(1)
      IZAXIS(NSIZE) = IAXIS(8)
      IZAXIS(NYZ) = IAXIS(IZDIF)
      WRITE(6,1)(IMINUS(J),J=1,NSIZE)
      NLINE = 1
C-----
      DO 20 NO=1,NP
      I = NOR(NO)
      IX = (X(I) - XMIN)/DX*XSIZE + 1.5
   32 IF(IX - NLINE) 30,33,34
C-----
   34 WRITE(6,4)(IZAXIS(J),J=1,NSIZE)
      NLINE = NLINE + 1
      GO TO 32
C-----
   33 NLINE = NLINE + 1
      IY = (Y(I) - YMIN)/DY*PLSIZE + 1.5
      IY = (Y(I) - YMIN)/DY*PLSIZE + 1.5
      IYB8 = IY/8
      IYDIF = IY - IYB8*8
      NY1 = IYB8 + 1
      IF(IYDIF.NE.0) GO TO 31
      NY1 = IYB8
      IYDIF = 8
   31 IPLOT(NY1) = IPOINT(IYDIF)
      IPLOT(1) = IAXIS(1)
      IPLOT(NSIZE) = IAXIS(8)
      IF(NY1.EQ.1) IPLOT(1) = IFIRST(IYDIF)
      IF(NY1.EQ.NSIZE) IPLOT(NSIZE) = ILAST(IYDI
      WRITE(6,2) X(I),Y(I),(IPLOT(J),J=1,NSIZE)
      IF(YMNMX.GE.0.0) GO TO 30
      WRITE(6,3)(IZAXIS(J),J=1,NSIZE)
   30 IPLOT(NY1) = IB
C-----
      WRITE(6,3)(IMINUS(J),J=1,NSIZE)
      RETURN
      END
```

```
FORTRAN IV G LEVEL  18              ORDER            DATE = 71088          20/00/33              PAGE 0001

              SUBROUTINE ORDER(POINTS,N,NORDER)
              DIMENSION POINTS(1),NORDER(1)
              DIMENSION X(225)
              DO 30 I=1,N
              NORDER(I) = I
           30 X(I) = POINTS(I)
              NM1 = N - 1
              DO 20 J=1,NM1
              IMIN = J
              JP1 = J + 1
              DO 10 I=JP1,N
           10 IF(X(I).LT.X(IMIN)) IMIN = I
              X(IMIN) = X(J)
              NIMIN = NORDER(IMIN)
              NORDER(IMIN) = NORDER(J)
           20 NORDER(J) = NIMIN
              RETURN
              END
```

```
0001          SUBROUTINE CURVFT(X,Y,N,NDEGX,C,ESQRMN)
        C-----
        C     +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
        C     +        SUBROUTINE CURVFT - LEAST SQUARES METHOD             +
        C     +                                                              +
        C     +        CALLING REQUIREMENTS                                  +
        C     +                                                              +
        C     +        X           ARRAY OF VALUES OF INDEPENDENT VARIABLE   +
        C     +        Y           ARRAY OF VALUES OF DEPENDENT VARIABLE     +
        C     +        N           DIMENSION OF X OR Y                       +
        C     +        NDEGX       MAXIMUM DEGREE OF POLYNOMIAL IN X         +
        C     +        C           RESULTING COEFFICIENT VECTOR FOR A FUNCTIONAL +
        C     +                    RELATION OF THE FORM Y = SUM( C(I)*(X**(I-1)) +
        C     +                                               I              +
        C     +        ESQRMN      MINIMUM SQUARED ERROR FOUND               +
        C     +                                                              +
        C     +        SUBPROGRAM REQUIREMENT                                +
        C     +        SIMQ        TO SOLVE LINEAR SIMULTANEOUS EQUATIONS (SSP) +
        C     +        PVAL        TO EVALUATE A POLYNOMIAL AT THE POINT X(SSP) +
        C     +                                                              +
        C     +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
        C-----
0002    77    FORMAT(1H1)
0003    66    FORMAT(1X,' X= ',F15.7,' Y= ',F15.7,' Y-CAL= ',F15.7,' DIFF= ',
             $F15.7,' PCT-DIFF= ',F15.7)
0004          DIMENSION X(1),Y(1),C(1),XKPNM1(21),A(121)
        C-----
0005          NXP1 = NDEGX + 1
0006          NXT2 = NDEGX*2
0007          LENTHA = NXP1*NXP1
        C-----
0008          DO 10 IC=1,NXP1
0009       10 C(IC) = 0.0
0010          DO 11 IA=1,LENTHA
0011       11 A(IA) = 0.0
        C-----
0012          DO 100 K=1,N
0013          XKPNM1(1) = 1.0
0014          IF(NXT2.EQ.0) GO TO 21
0015          DO 20 IX=1,NXT2
0016       20 XKPNM1(IX+1) = XKPNM1(IX)*X(K)
        C-----
0017       21 DO 100 IP=1,NXP1
0018          IARG = IP - NXP1
0019          DO 30 I=1,NXP1
0020          IARG = IARG + NXP1
0021       30 A(IARG) = A(IARG) + XKPNM1(IP+I-1)
0022      100 C(IP) = C(IP) + Y(K)*XKPNM1(IP)
        C-----
0023          IF(NXP1.GT.1) GO TO 41
0024          C(1) = C(1)/A(1)
0025          GO TO 42
0026       41 CALL SIMQ(A,C,NXP1,0)
        C-----
0027       42 ESQRMN = 0.0
0028          WRITE(6,77)
0029          DO 40 K=1,N
0030          CALL PVAL(YK,X(K),C,NXP1)
```

```
      DIFF=Y(K)-YK
      PDIFF=DIFF*100.00/Y(K)
      WRITE(6,66)X(K),Y(K),YK,DIFF,PDIFF
   40 ESQRMN = ESQRMN + (Y(K) - YK)*(Y(K) - YK)
      WRITE(6,77)
C-----
      RETURN
      END
```

APPENDIX E

APPLICATION OF DIMENSIONAL ANALYSIS TO THE PROPOSED MODEL

The method of dimensional analysis has been in widespread use mostly by physicists and engineers from the time of Newton. Since then, the works of Fourier, Clark-Maxwell, Buckingham, Bridgman and recently, that of Drobot and Langhaar have greatly enhanced its application to various types of problems ranging from mechanics to heat transfer, scale modeling to diffraction of light and kinematics to aerodynamics (108). Bridgman (109) has described the purpose of dimensional analysis thus:

> ... to give certain information about the relations which hold between the measurable quantities associated with various phenomena ... In dealing with any phenomena or group of phenomena our method is as follows: We first measure certain quantities which we have some reason to expect to be of importance in describing the phenomenon. These quantities which we measure are of different kinds and for each of these, we have different rule of operation by which we measure it, that is, associate the quantity with a numer... Then we search for relations between these numbers, and if we are skillful and fortunate, we find relations which can be expressed in mathematical form. We are usually interested pre-eminently in one of the measured quantities and try to find it in terms of the others. Under such conditions we would search for a relation of the form:
>
> $$X_1 = \emptyset\ (X_2, X_3, X_4, \ldots X_n)$$
>
> where X_i stands for the numbers which are measures of particular kinds of physical quantity.

Economists seldom apply the concept of dimension in an explicit way. There are, however, some exceptions: Jevons (110) tried to define economic dimensions as early as 1879; also, Evans (111), Brems (112), Allais (113), Ryde (114) and Boulding (115) have treated economic concepts in terms of dimensions. De Jong (116) is perhaps the first economist to rigorously apply and demonstrate the usefulness of dimensional analysis in his book entitled, "Dimensional Analysis for Economists" (116). By defining several primary economic dimensions, he derived dimensional groupings and verified several economic concepts such as rate of inflation, demand function for an economic good, supply of labor and the technological parameters in the production functions of Cobb and Douglass, and Arrow, Chenergy, Minhas and Solow, etc.

Before applying dimensional analysis to the proposed model described by equation (IV.9), given below, it is proposed to derive a set of dimensions for the six techno-economic parameters.

$$E = (GNP) \cdot \left(\frac{P}{W}\right) \cdot \left(\frac{\tau}{\rho}\right) \qquad (IV.9)$$

<u>A Set of Proposed Dimensions for the Model</u>

De Jong formulated a set of primary and secondary economic dimensions and applied them to various macro-economic theories such as, Fisher's equation of exchange $(MV = PT)$; Keynesian theory relating national income to consumption and investment $(Y = C + 1)$; Cassel's theory of aggregate production and the micro-economic theory by Pareto which related production functions with ophelimity functions. In the past, physicists and engineers have contended themselves with four primary dimensions: mass, length, time and heat (108,117). The matter is not so simple with respect to economics because it is impossible for economists to define just one set of primary economic dimensions for use in every conceivable case. For example, primary dimensions in micro-economic analysis may differ from those in macro-economic analysis if the latter involves quantities which are not aggregated micro-economic quantities (118). The following discussion is aimed at defining the dimensions for the six parameters used in the formulation of the proposed model.

Dimension For Gross National Product (GNP) (1)

The output of an economy is defined in terms of an equivalent stock of money (M), taken as a dimension. This represents the dollar value of all goods and services produced per unit of time and evaluated at current prices. De Jong (119) has shown that the gross national product has the dimension $\frac{[M]}{[T]}$.

Dimensions For Population (P) and Total Energy (E) (2,3)

These are taken as a number and heat per unit time, respectively.

Dimension For Labor (4)

Perhaps the simplest macro-economic model of an economy is represented by Fisher's equation of exchange $MV = PT$ (described on page 50); the variable T denotes "Trade Volume" or the flow of goods. This definition is a rough approximation since it considers all kinds of goods lumped together and no distinction is made between labor, costumes, cars, rice, potatoes, etc. They are considered to be additive quantities and their sum total T, sold per unit of time, is denoted by a primary dimension [R]. However, Keynes has distinguished between consumption goods, investment goods and labor. Therefore, three secondary dimensions - $[R_c]$, $[R_i]$, $[R_l]$ - have been defined to denote consumption goods, investment goods and labor respectively. Keynes (118) further stated,

> The quantity of employment can be sufficiently defined for our purpose by taking an hour's employment of ordinary labor as our unit ... we shall call the unit in which the quantity of employment is measured the labor-unit, and the money wage of a labor unit we shall call the wage-unit. Thus if W is the wages (and salaries) bill, w the wage-unit, and N_d the quantity of employment, $W = wN_d$.

This means that a stock of labor could be defined as number of man-hours and, the set of all man-hours may be considered as the dimension $[R_l]$ of labor employed. The wage level is then the price of labor and its dimension becomes $[M \cdot R_l^{-1}]$. If a given wage bill is required to represent a flow of stock of money $[M]$, then,

$$W \in [MT^{-1}] \tag{E.1}$$

and, the quantity of employment should then be measured, not in terms of man-hours, but in man-hours per unit of time (e.g., per week or per year) so that the dimension for labor as a quantity of employment will be $[R_l\ T^{-1}]$. It should be appreciated that the dimension $[R_l]$, defined as man-hours per unit of time is not to be confused with ordinary calendar time for which a primary dimension of $[T]$ has already been established. It is obvious that several secondary units of time could be used for the quantity of employment: man-hours per week, man-hours per year or man-hours per month. This would not be true if man-hours and time belonged to the same dimension (119).

Ackley (120) has also considered this matter,

> If we deflate aggregate wages and salaries (W) by an index of wage and salary rates (w), we come out with a measure of time worked - of input not income.

In terms of dimensions, it can be written as:

$$W \in [MT^{-1}] \tag{E.2}$$

$$w \in [MR_1^{-1}] \tag{E.3}$$

and therefore,

$$\frac{W}{w} \in \frac{[MT^{-1}]}{[MR_1^{-1}]} = [R_1 \ T^{-1}] \tag{E.4}$$

This is obviously not an income but a flow of labor. Therefore, the dimension for labor taken as a quantity of employment will be $[R_1 \ T^{-1}]$.

Dimension For Economic Productivity Reflecting Technological Change (5)

The technological change parameter in the production function of Cobb and Douglass (121) is given by the equation:

$$u = C_a \cdot N^{\alpha} \cdot K_a^{1-\alpha} \tag{E.5}$$

where,

- u represents the rate of production
- N represents the employment
- K_a represents the stock of real capital in use
- C_a represents technical knowledge or the "state of arts." In the short run, C_a may be considered a constant, but in the long run, its value varies according to changes in technology, organization, quality of capital goods, skill of labor, etc.

α represents a numerical constant.

Arrow, Chenery, Minhas and Solow (122) have extended the above equation to separately account for productivity of labor and capital. Their linear homogeneous production function, with constant elasticity of substitution (CES), is given as:

$$u = (C_{aN}N^{\alpha} + C_{aK}K_a^{\alpha})^{\frac{1}{\alpha}} \tag{E.6}$$

Where C_{aN} and C_{aK} represent technological parameters for labor and capital productivities respectively, they are specified as linear and homogeneous functions:

$$u = \{u^{\alpha-1} \cdot u\} \tag{E.7}$$

$$= \left[u^{\alpha-1} \cdot \left(\frac{\partial u}{\partial N} \cdot N + \frac{\partial u}{\partial K_a} \cdot K_a\right)\right]^{\frac{1}{\alpha}} \tag{E.8}$$

$$= \left(\frac{\partial u}{\partial N} \cdot \frac{u^{\alpha-1}}{N^{\alpha-1}} \cdot N^{\alpha} + \frac{\partial u}{\partial K_a} \cdot \frac{u^{\alpha-1}}{K_a^{\alpha-1}} \cdot K_a^{\alpha}\right)^{\frac{1}{\alpha}} \tag{E.9}$$

By comparison with equation (E.6):

$$C_{aN} = \frac{\partial u}{\partial N}\left(\frac{u}{N}\right)^{\alpha-1} \tag{E.10}$$

therefore,

$$C_{aN}^{\frac{1}{\alpha}} = \left[\frac{\partial u}{\partial N} \cdot \left(\frac{u}{N}\right)^{\alpha-1}\right]^{\frac{1}{\alpha}} \tag{E.11}$$

and,

$$C_{aK} = \frac{\partial u}{\partial K_a} \cdot \left(\frac{u}{K_a}\right)^{\alpha-1} \tag{E.12}$$

therefore,

$$C_{aN}^{\frac{1}{\alpha}} = \left[\frac{\partial u}{\partial K_a} \cdot \left(\frac{u}{K_a}\right)^{\alpha-1}\right]^{\frac{1}{\alpha}} \tag{E.13}$$

This means that the technological parameter multiplying the αth power of a factor of production represents the marginal physical productivity of that factor of production multiplied by the $(\alpha-1)$th power of its average physical productivity.

The parameter C_{aN} may change as a result of, for instance, more investment in men yielding a better skill of labor. Thus allowing for changes in the quality of labor, the changes in the quantity of labor (in terms of say man-years) can be measured. Therefore, changes in C_{aN} and C_{aK} - the two technological parameters - express changes in technology in the broadest sense. In Solow's (104) words:

> It will be seen that I am using the phrase "technical change" as a short hand expression for any kind of shift in the production function. Thus slowdowns, speedups, improvements in the education of the labor force and all sorts of things will appear as technical change. It is convenient to begin with the special case of neutral technical change. Shifts in the production function are defined neutral if they leave marginal rates of substitution untouched but simply increase or decrease the output attainable from given inputs.

In view of the foregoing remarks, the dimension for technological change is calculated to be:

$$\left[\frac{R_p \cdot R_K}{R_1 \cdot T}\right]$$

Dimension For Price Per Unit of Energy (6)

This is by definition, taken as $[MH^{-1}]$.

The generalized version of the proposed techno-economic model is described earlier by the equation (IV.10);

$$(E)^{a} = (GNP)^{b} \cdot \left(\frac{P}{W}\right)^{c} \cdot \frac{(\tau)^{d}}{(\rho)^{e}} \tag{E.14}$$

The substitution of the respective dimensions for the six parameters in the above equation results in the following dimensional equation:

$$\left[\frac{H}{T}\right]^{a} = \left[\frac{M}{T}\right]^{b} \cdot \left[\frac{(\text{a number})}{(R_{\ell} \cdot T^{-1})}\right]^{c} \cdot \left(\frac{R_{P} \cdot R_{K}}{R_{\ell} \cdot T}\right)^{d} \cdot \left(\frac{1}{MH^{-1}}\right)^{e} \tag{E.15}$$

In the above equation a, b, c, d and e are numerical exponents. These can be determined by applying Buchingham's theorem. By equating the exponents of the dimensions [H], [T], [M], and [R] on both sides of the above equation, the following set of identities result:

$$[H]^{a} = [H]^{e} \tag{E.16}$$

$$[T]^{-a} = [T]^{-b+c-d} \tag{E.17}$$

$$[M]^{o} = [M]^{b-e} \tag{E.18}$$

and,

$$[R]^{o} = [R]^{-e+2d-d} \tag{E.19}$$

Solution of the above four equations (E.16) to (E.19) it is seen that:

$$a = e = b$$

$$c = d \tag{E.20}$$

By plotting various groupings of the six variables in the model, the values for the exponents are found to be:

$$a = e = b = 1$$

and

$$c = d = 1 \tag{E.21}$$

Therefore, the dimensional homogenity of the proposed techno-economic model is established. The justification to subject the proposed model to Buckingham's theorem is summarized in the words of Bridgman (109) thus:

> The principle use of dimensional analysis is to deduce from study of the dimensions of the variables in any physical system certain necessary limitations on the form of any possible relationship between those variables. The method is of great generality and mathematical simplicity ... This method is not capable of determining the unknown functional relationship. In the simplest cases it can give everything except a numerical factor of proportionality ... In more complicated cases, where there are a large number of variables, it can show that the variables must enter the function in certain definite combinations, thus reducing the number of undetermined functional relations. Perhaps its most important use is in connection with problems so complicated that not only may an exact solution by purely mathematical methods be impossible, but also it may be impossible even to give a precise and detailed formulation of the fundamental equations from which the solution can be found. Many problems of aeroplane or ship design are of this nature. In these cases, a knowledge of the necessary limitations on any possible functional makes it possible to cover completely the range of all possible experimental relationships with a much smaller number of experiments than would be necessary otherwise.

APPENDIX F

TECHNOLOGICAL AND ECONOMIC PROSPECTS FOR INTER-FUEL SUBSTITUTION TO THE YEARS 1980 AND 2000

The purpose of this Appendix is to assess the relative shares of various energy sources (fuels) to meet the U.S. total energy requirements forecast for the years 1980 and 2000. The assumption of adequacy of energy supplies to meet the forecast demand to the year 2025 is also relaxed herein to ascertain its validity.

The process of inter-fuel substitution is a special case of the overall process of substitution which reflects the needs of society and also acts as an instrument of societal change. Although the agents for both types of substitution are quite similar, the technological and economic prospects play by far a greater role in determining the patterns of inter-fuel substitution. From a policy-making standpoint, the process of inter-fuel substitution determines, to a large extent, the energy-mix for a given economy.

Technological Prospects for Inter-Fuel Substitution

Technological prospects for inter-fuel substitution result from either improvements to and/or replacements of existing technology. This is generally evidenced as improvements in technical plant efficiency, energy conversion technology, favorable circumstances of inter-fuel substitution/competition and, in some cases, the substitution of capital equipment for energy as a factor of production. For this latter case, there is a certain range over which the capital-energy substitution can take place; their relative prices determine, at least in part, the particular capital-energy combination used in a production process. In the case of technological advancement, progress can occur both horizontally and vertically. Horizontal changes characterize the spread of technical knowledge whereas vertical changes refer to the level at which the technological knowledge is applied. In the case of U.S., for example, Strout (53) has calculated that if the technology prevalent in 1939 had continued through 1954, the economy would have required an additional input of 9.3×10^{15} BTU or 24 percent of the total energy demand in 1954.

The processes of inter-fuel substitution, though subtle, have proceeded continuously. Theoretically speaking, the extent to which a given fuel may be replaced by other fuels, or vice versa, depends, interalia, upon their relative technical (conversion) efficiencies and price-cost relationships.

Some economists have estimated that about 35 to 40 percent of the total U.S. current energy requirements could be met by any of a group of fossil fuels. While this may be technically true, it could only be accomplished if tremendous capital investments were to be made in new energy conversion plants. The anticipated expense of converting the existing plants, in view of their reduced efficiency, may be much more than the expenses of installing new plants. For example, crude petroleum may be substituted for coal under a boiler, but then the so-called technical (conversion) efficiency will be extremely limited.

Then there is the additional factor of human convenience which can be of significant importance in inter-fuel substitution. This factor is in conformity with the overall objective of technology to develop new products and processes rendering increased convenience. The patterns of inter-fuel substitution which have occurred in the U.S. during the past century illustrate the significance of this factor. Because wood could not be produced and converted as efficiently and conveniently as coal, its displacement by coal was inevitable. Also, because of the unique physical and chemical properties of petroleum, its preference and eventual replacement of coal is easily understood. Since natural gas offers even greater convenience and versatility than petroleum, it may have been substituted except for shortages in natural gas supplies. Finally, electricity, the most convenient form of energy although in an inanimate form, appears to be headed for a majority share in the U.S. energy-mix.

In view of the foregoing remarks, it is assumed that several new technological developments will be evidenced during the period 1980-1990. Perhaps the most important of all will be the introduction of the Breeder Reactor (123) on the U.S. energy scene in the mid-eighties. This is assumed to occur largely in response to the ever-increasing demand for electricity, in spite of the increasing pressure from environmentalists.[14] Also, it is assumed that by the end of the current

[14]Here a distinction is made between the roles of an environmentalist and an ecologist; it is similar to that of a druggist and a doctor.

decade, the introduction of a 'non-polluting automobile' will find itself in a relatively more favorable political and industrial climate. Such an automobile may be fueled by electricity, steam or hydrogen (124, 125). All such cases, however, are expected to lead to structural changes in the current patterns of energy consumption for the transportation sector of the economy.

Economic Prospects for Inter-Fuel Substitution

The economic factors affecting inter-fuel substitution are easy to discern but difficult to analyze. Traditional economics attempts to explain major shifts in inter-fuel substitution in terms of relative price-cost ratios of the various fuels. However, historical data on changes in "real" prices of fuels, in many instances, do not justify such a generalization. In one instance, for example, during 1947-1967, natural gas substantially increased its share in the energy mix of the U.S. Contrary to popular view, its index of relative price in constant dollars however, also increased (from 100 in 1947 to 211 in 1967). Therefore, relative price indices or relative price-cost mechanisms can not be entirely relied upon for a complete analysis of inter-fuel substitution patterns (9). Instead several additional factors have to be weighed for a complete analysis. Some of these factors are general economic fluctuations in an economy, cost-induced changes in the international energy market, considerations of environmental quality, and changes in governmental regulatory policies.

Temporary fluctuations in the economic climate of the U.S. energy intensive economy can often have different effects on the demand of different fuels. Demand for electricity, diesel oil and gasoline, for example, can be directly correlated with the rate of industrial output. Sometimes, the rate of increase in the overall efficiency of energy use (in other words, a decrease in energy-intensity), tends to accelerate during economic downturns. This is probably because output may, at such times, be concentrated in more efficient plants, and because obsolete plants may be scrapped. For a similar reason, some energy-intensive industries, like the iron and steel, fare badly in such times of economic slow-down. Furthermore, the output of certain industries (iron, steel and construction) requires disproportionately heavy amounts of energy. Therefore, it seems necessary to consider the general economic level of activity as a variant of inter-fuel substitution. Lastly, the dealings of the international companies with major petroleum exporting countires of the world, have been recently evidenced to have far-reaching consequences in the markets of the consuming countries. Should the cost of oil be increased before leaving an exporting country, changes in price/cost can be anticipated at all levels. With regard to the difficult question of allowing for purely market-induced or intrinsically cost-induced price changes for energy,[15] it is common practice to consider all such changes in terms of the ratio of the price of fuel in question to that of a fuel whose price has not changed. Such a ratio quantifies the inter-fuel substitution pattern.

So much for the internationally-induced price changes. Here, within the U.S., there are two additional economic factors which can seriously affect patterns of fuel supply and hence of inter-fuel substi-

[15] It is obvious that a labor-intensive industry is less free to reduce its prices to stimulate demand than one which is more elastic in its cost allocation and structure.

tution. Firstly, there is the question of governmental policies which may, in effect, restrict or narrow the range of incentives for exploration. Secondly, there are the governmental price regulations. The increased tax burden of $700 million in 1970, and the 16-year long federal practice of regulating natural gas prices are some of the reasons given for recent natural gas shortages in the U.S. (126). In the same vein, if federal regulations were to be introduced in the areas of de-sulphurization and de-leading of fuels, prices of coal and gasoline are most likely to further increase.

Since the issues discussed above cannot be precisely anticipated, no quantitative formulae can be advanced to forecast the economic prospects for inter-fuel substitution. However, if price data relating to the three main fossil fuels are analyzed for the period 1950 to 1965, it can be seen that the price index for coal has decreased and the price indices for crude oil, natural gas and Bunker "C" fuel oil have increased. Their relative trends can be forecast to continue through the years 1980 and 2000; through the years 1980 and 2000; the resulting patterns of the energy mix are shown in Figure 26.

Adequacy of Energy Supplies

Throughout this study, it has been assumed that adequate energy supplies will be available during the forecast period 1970-2025. In the following analysis, this assumption is further examined for its validity.

Given the total energy consumption for the U.S. in a base year as E_1, and assuming a constant rate of increase (r) percent per year, over a period of (n) years, the cumulative energy requirements (E_c)

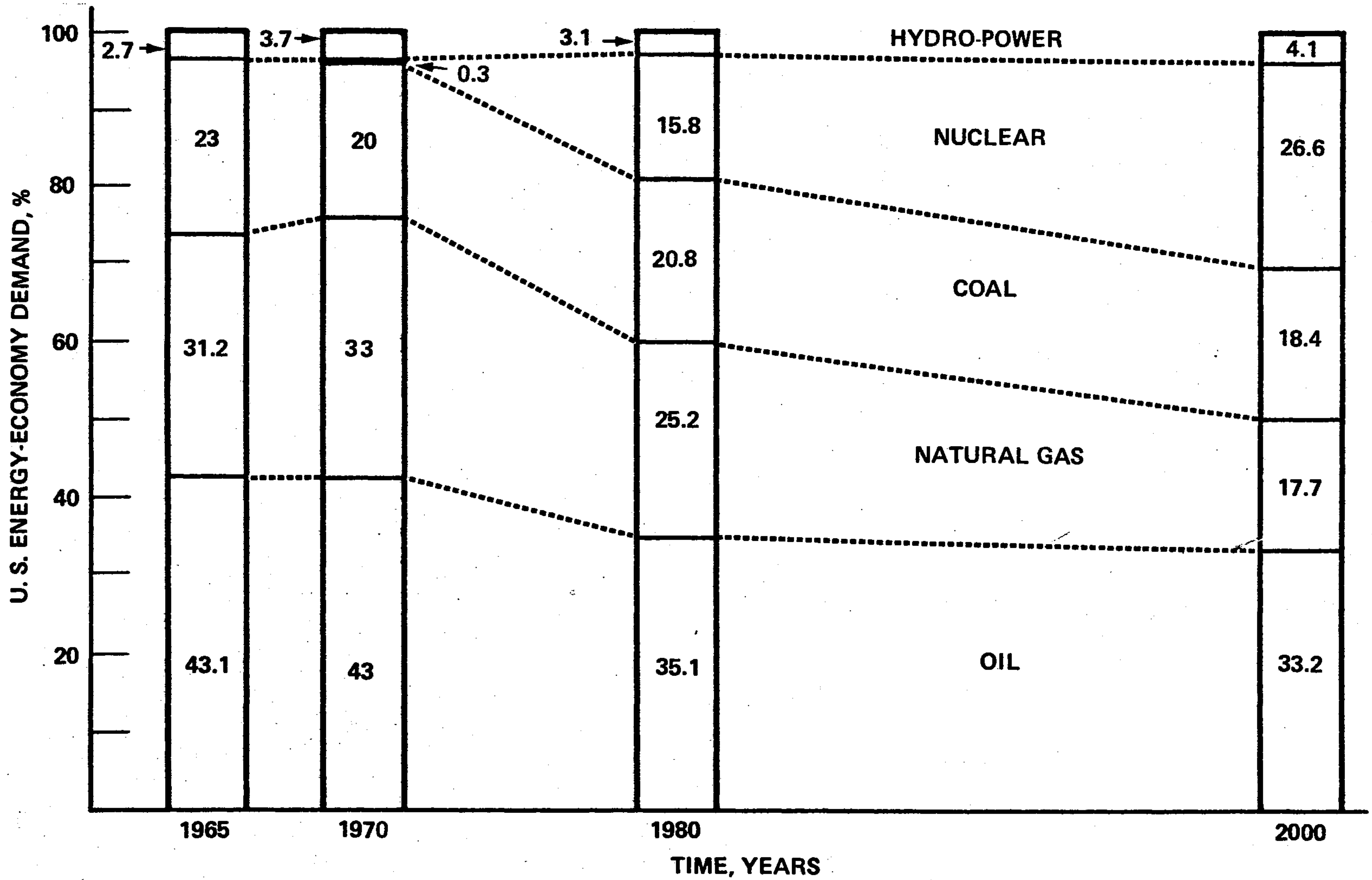

FIGURE 26. PATTERNS OF INTER-FUEL SUBSTITUTION FORECAST FOR THE U.S. ECONOMY, (1980-2000)

during the forecast period is calculated by the equation:

$$E_c = \int_o^n (E_i) \cdot (1 + r)^n dn \qquad \text{(F-1)}$$

or,

$$E_c = \frac{E_i}{\log_e (1 + r)} \cdot \left[(1 + r)^n - 1\right] \qquad \text{(F-2)}$$

The U.S. total energy consumption (E_i) in 1970 is reported as 68.810 quadrillion (10^{15}) BTU (47); and the value forecast by this study for the year 2025 is 300.3 quadrillion BTU. During the fifty-five year forecast period, therefore, the rate of increase in energy requirements is calculated to be 2.65 percent per year.[16] Substituting the appropriate values in equation (F-2) above, the cumulative energy requirements during the period 1970-2025 is calculated as:

$$\begin{aligned} E_c &= \frac{68.810 \times 10^{15}}{\log_e (1 + 0.0265)} \cdot \left[(1 + 0.0265)^{55} - 1\right] \\ &= 8,475 \times 10^{15} \text{ BTU} \\ &= 8.475 \text{ Q } \ (1\text{Q} = 10^{18}) \text{ BTU} \qquad \text{(F-3)} \end{aligned}$$

Table V shows an inventory of the ultimate potential reserves (R_∞)[17] of U.S. primary energy sources (excluding solar and nuclear

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[16]If this rate was assumed as 3 percent per year, the value for E_c comes to 9.84×10^{18} BTU.

[17]This estimate implies the exploitation of energy resources with those technological advancements which may be evidenced in the future.

TABLE V

ESTIMATE OF ULTIMATE POTENTIAL RESERVES (R_∞) OF U.S. PRIMARY ENERGY SOURCES, EXCLUDING SOLAR[18] AND NUCLEAR[19]

	ENERGY SOURCE	BIBLIO-GRAPHY REFERENCE	ESTIMATE (R_∞) Common Units	$\times 10^{18}$, BTU
1	Petroleum	127	250×10^9 barrels	1.45
2	Natural gas plus liquids	128	1500×10^{12} ft.^{3}	1.90
3	Coal	129	1500×10^9 metric tons	34.40
4	Oil shales	130		3.81
5	Hydro-power	131	161×10^3 Mw	0.01
6	Tidal power	132		<0.01
7	Geothermal	133		<0.01
			TOTAL	41.58 Q

[18] The estimates for Solar energy reported so far are too qualitative to permit a fairly reasonable quantification.

[19] Weinberg and Hammond (134) have eloquently discussed the nuclear energy prospects.

sources) as 41.58 Q (10^{18}) BTU. The forecast for U.S. cumulative energy requirements by equation (F-3), during 1970-2025, is seen to be about 20 percent of the value of (R_∞), given in Table V. Therefore, adequate energy supplies are ensured during the forecast period.

Equation (F-2) may also be used to calculate the ultimate time span for the exhaustion of fossil fuel reserves in the U.S. Assuming (E_c) to be 40Q, and the rate of total energy consumption to increase at about 3 percent per year, equation (F-2) gives a time span of about a century.

APPENDIX G

DATA USED FOR THE MODEL

TABLE VI

U.S. DATA FOR VARIOUS TECHNO-ECONOMIC PARAMETERS

YEAR	TOTAL ENERGY CONSUMPTION [E], QUADRILLION (10^{15}) BTU	GROSS NATIONAL PRODUCT, [GNP] CURRENT-\$ $\times 10^9$	GROSS NATIONAL PRODUCT, [GNP] OF 1958-\$ $\times 10^9$
1915	18.10	61.6	135.2
1916	20.09	68.7	153.2
1917	21.48	75.6	168.6
1918	21.39	77.3	172.4
1919	20.09	78.9	175.9
1920	21.59	88.9	180.1
1921	18.49	74.0	165.0
1922	19.34	74.0	165.0
1923	23.32	86.1	192.0
1924	22.38	87.6	195.3
1925	22.10	91.3	203.6
1926	22.38	97.7	217.9
1927	23.68	96.3	214.7
1928	23.71	98.2	219.0
1929	23.17	103.1	203.6
1930	21.89	90.4	183.5
1931	20.61	75.8	169.3
1932	20.05	58.0	144.2
1933	19.50	55.6	141.5
1934	20.45	65.1	154.3
1935	21.40	72.2	169.5
1936	22.17	82.5	193.0
1937	22.94	90.4	203.2
1938	21.68	84.7	192.9
1939	22.46	90.5	209.4

TABLE VI (Continued)

YEAR	TOTAL ENERGY CONSUMPTION [E], QUADRILLION (10^{15}) BTU	GROSS NATIONAL PRODUCT, [GNP] CURRENT-\$ $\times 10^9$	GROSS NATIONAL PRODUCT, [GNP] OF 1958-\$ $\times 10^9$
1940	25.81	99.7	227.2
1941	26.78	124.5	263.7
1942	27.19	157.9	297.8
1943	29.80	191.6	337.1
1944	30.42	210.1	361.3
1945	30.20	211.9	355.2
1946	29.92	208.5	312.6
1947	33.20	231.3	309.9
1948	34.01	257.6	323.7
1949	31.61	256.5	324.1
1950	34.20	284.8	355.3
1951	36.91	328.4	383.4
1952	36.61	345.5	395.1
1953	37.70	364.6	412.8
1954	36.40	364.8	407.0
1955	40.01	398.0	438.0
1956	42.01	419.2	446.1
1957	41.91	441.1	452.5
1958	42.01	447.3	447.3
1959	43.5	483.7	475.9
1960	45.31	503.7	487.7
1961	45.60	520.1	497.2
1962	47.71	560.3	529.8
1963	49.70	590.5	551.0
1964	51.60	632.4	581.1
1965	53.80	684.9	617.8
1966	56.61	747.6	657.1
1967	59.40	789.7	673.1
1968	62.11	860.7	706.9
1969	65.6	931.1	727.4
1970	68.81	998.7	724.3

TABLE VII

U.S. DATA FOR VARIOUS TECHNO-ECONOMIC PARAMETERS

YEAR	NATIONAL INCOME, $[Y_N]$ CURRENT $, $\times 10^9$	PERSONAL INCOME $[Y_P]$ CURRENT $ $\times 10^9$	INDUSTRIAL PRODUCTION INDEX $[\tau]$ (1957-59 = 100)
1915	54.0	51.0	22.1
1916	60.4	56.7	22.8
1917	66.9	62.5	23.5
1918	68.5	63.7	24.2
1919	70.2	65.0	24.9
1920	79.1	73.4	26.2
1921	64.0	62.1	20.1
1922	63.1	62.0	25.6
1923	74.3	71.5	30.5
1924	75.2	73.2	28.6
1925	78.2	75.0	31.5
1926	83.7	79.5	33.4
1927	81.7	79.6	33.3
1928	82.8	79.8	34.6
1929	86.8	85.9	38.4
1930	75.4	77.0	32.0
1931	59.7	65.9	26.5
1932	42.8	50.2	20.7
1933	40.3	47.0	24.4
1934	49.5	54.0	26.6
1935	57.2	60.4	30.7
1936	65.0	68.6	36.3
1937	73.6	74.1	39.7
1938	67.4	68.3	31.4
1939	72.6	72.8	38.3
1940	81.1	78.3	43.9
1941	104.2	96.0	56.4
1942	137.1	122.9	69.3
1943	170.3	151.3	82.9
1944	182.6	165.3	81.7
1945	181.5	171.1	70.5
1946	181.9	178.7	59.5
1947	199.0	191.3	65.7
1948	224.2	210.2	68.4
1949	217.5	207.2	64.7
1950	241.1	227.6	74.9
1951	278.0	255.6	81.3
1952	291.4	272.5	84.3
1953	304.7	288.2	91.3
1954	303.1	290.1	85.8

TABLE VII (Continued)

YEAR	NATIONAL INCOME, $[Y_N]$ CURRENT \$, $\times 10^9$	PERSONAL INCOME $[Y_P]$ CURRENT \$ $\times 10^9$	INDUSTRIAL PRODUCTION INDEX $[\tau]$ (1957-59 = 100)
1955	331.0	310.9	96.6
1956	350.8	330.0	99.9
1957	366.1	351.1	100.7
1958	367.8	361.2	93.7
1959	400.0	383.5	105.6
1960	414.5	401.0	108.7
1961	427.3	416.8	109.7
1962	457.7	442.6	118.3
1963	481.9	465.5	124.3
1964	518.1	497.5	132.3
1965	564.3	538.9	143.4
1966	620.8	586.8	156.3
1967	652.9	628.8	151.4
1968	712.8	685.8	158.1
1969	769.5	748.9	172.4
1970	810.0	801.0	182.0

TABLE VIII

U.S. DATA FOR VARIOUS TECHNO-ECONOMIC PARAMETERS

YEAR	ALL ITEMS CONSUMER PRICE INDEX (1957-59 = 100)	WHOLESALE PRICE INDEX FOR ALL COMMODITIES [$\rho_{a \cdot c}$] (1957-59 = 100)	WHOLESALE PRICE INDEX FUELS AND RELATED PRODUCTS AND POWER [ρ_f] (1957-59 = 100)
1915	35.4	38.0	38.0
1916	38.0	46.8	54.6
1917	44.7	64.3	77.4
1918	52.4	71.7	80.2
1919	60.3	75.8	76.6
1920	69.8	84.5	120.3
1921	62.3	53.4	71.1
1922	58.4	52.9	78.8
1923	59.4	55.1	71.5
1924	59.6	53.6	67.6
1925	61.1	56.6	70.9
1926	61.6	54.8	73.5
1927	60.5	52.3	64.9
1928	59.7	53.0	61.9
1929	59.7	52.1	61.5
1930	58.2	47.3	58.2
1931	53.0	39.9	50.0
1932	47.6	35.6	52.1
1933	45.1	36.1	49.3
1934	46.6	41.0	54.3
1935	47.8	43.8	54.5
1936	48.3	44.2	56.5
1937	50.0	47.2	57.5
1938	49.1	43.0	56.6
1939	48.4	42.2	54.2
1940	48.8	43.0	53.2
1941	51.3	47.8	56.6
1942	56.8	54.0	58.2
1943	60.3	56.5	59.9
1944	61.3	56.9	61.6
1945	62.7	57.9	62.3
1946	68.0	66.1	66.7
1947	77.8	81.2	79.7
1948	83.8	87.9	93.8
1949	83.0	83.5	89.3

TABLE VIII (Continued)

YEAR	ALL ITEMS CONSUMER PRICE INDEX (1957-59 = 100)	WHOLESALE PRICE INDEX FOR ALL COMMODITIES [$\rho_{a \cdot c}$] (1957-59 = 100)	WHOLESALE PRICE INDEX FUELS AND RELATED PRODUCTS AND POWER [ρ_f] (1957-59 = 100)
1950	83.8	86.8	90.2
1951	90.5	96.7	93.5
1952	92.5	94.0	93.3
1953	93.2	92.7	95.9
1954	93.6	92.9	94.6
1955	93.3	93.2	94.5
1956	94.7	96.2	97.4
1957	98.0	99.0	102.7
1958	100.7	100.4	98.7
1959	101.5	100.6	98.7
1960	103.1	100.7	99.6
1961	104.2	100.3	100.7
1962	105.4	100.6	100.2
1963	106.7	100.3	99.8
1964	108.1	100.5	97.1
1965	109.9	102.5	98.9
1966	113.1	105.9	101.3
1967	116.3	106.1	103.6
1968	120.9	108.7	102.5
1969	119.2	105.4	104.3
1970	116.1	108.6	106.3

TABLE IX

U.S. DATA FOR SELECT TECHNO-ECONOMIC PARAMETERS (1915-1970), AND FORECAST VALUES TO THE YEAR 2025

YEAR	GROSS NATIONAL PRODUCT [GNP], (1958-$) × 10^9	TOTAL POPULATION [P], × 10^6	TOTAL LABOR FORCE EMPLOYED [W], × 10^6	F.R.B. INDEX OF INDUSTRIAL PRODUCTION [τ], (1958 = 100)	AVERAGE PRICE OF ENERGY (FUEL) PER MILLION BTU [ρ_f], 1958-$ (1958 = 100)	TOTAL ENERGY CONSUMED [E], QUADRILLION (10^{15}) BTU
1915	135.2	100.54	39.77	22.1	29.8	18.09
1920	180.1	106.46	41.72	26.2	35.9	21.59
1925	183.6	115.83	41.19	31.5	52.1	22.09
1930	183.5	123.18	48.73	32.0	58.2	21.90
1935	169.5	127.36	52.55	30.7	53.8	21.40
1940	227.2	132.12	56.18	43.9	53.2	25.80
1945	355.2	139.92	65.30	70.5	62.3	30.20
1950	355.3	151.68	64.74	74.9	80.2	34.20
1955	438.0	165.27	68.89	96.6	94.5	40.01
1960	487.7	180.68	73.12	108.7	99.6	45.30
1965	617.8	194.57	74.31	143.4	98.9	53.80
1968	726.9	200.44	75.91	158.1	103.1	62.10
1970	724.3	204.80	78.40	182.0	106.3	68.81
1980	1,280	245	100	246.8	132.8	91.1
1990	1,996	287	119	341.1	155.0	122.8
2000	3,115	322	134	564	185.8	169.2
2025	7,455	422	173	1,456	348.3	300.3

VITA

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